Geant4 User's Guide for Application Developers

Version: geant4 9.3

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Geant4 Collaboration

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by Geant4 Collaboration

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Chapter 1. Introduction

1.1. Scope of this manual

The User's Guide for Application Developers is the first manual the reader should consult when learning about Geant4 or developing a Geant4-based detector simulation program. This manual is designed to:

- introduce the first-time user to the Geant4 object-oriented detector simulation toolkit,
- provide a description of the available tools and how to use them, and
- supply the practical information required to develop and run simulation applications which may be used in real experiments.

This manual is intended to be an overview of the toolkit, rather than an exhaustive treatment of it. Related physics discussions are not included unless required for the description of a particular tool. Detailed discussions of the physics included in Geant4 can be found in the Physics Reference Manual. Details of the design and functionality of the Geant4 classes can be found in the User's Guide for Toolkit Developers, and a complete list of all Geant4 classes is given in the Software Reference Manual.

Geant4 is a completely new detector simulation toolkit written in the C++ language. The reader is assumed to have a basic knowledge of object-oriented programming using C++. No knowledge of earlier FORTRAN versions of Geant is required. Although Geant4 is a fairly complicated software system, only a relatively small part of it needs to be understood in order to begin developing detector simulation applications.

1.2. How to use this manual

A very basic introduction to Geant4 is presented in **Chapter 2, "Getting Started with Geant4 - Running a Simple Example"**. It is a recipe for writing and running a simple Geant4 application program. New users of Geant4 should read this chapter first. It is strongly recommended that this chapter be read in conjunction with a Geant4 system installed and running on your computer. It is helpful to run the provided examples as they are discussed in the manual. To install the Geant4 system on your computer, please refer to the Installation Guide for Setting up Geant4 in Your Computing Environment.

Chapter 3, "Toolkit Fundamentals" discusses generalGeant4 issues such as class categories and the physical units system. It goes on to discuss runs and events, which are the basic units of a simulation.

Chapter 4, "Detector Definition and Response" describes how to construct a detector from customized materials and geometric shapes, and embed it in electromagnetic fields. It also describes how to make the detector sensitive to particles passing through it and how to store this information.

How particles are propagated through a material is treated in **Chapter 5, "Tracking and Physics"**. The Geant4 "philosophy" of particle tracking is presented along with summaries of the physics processes provided by the toolkit. The definition and implementation of Geant4 particles is discussed and a list of particle properties is provided.

Chapter 6, "User Actions" is a description of the "user hooks" by which the simulation code may be customized to perform special tasks.

Chapter 7, "Communication and Control" provides a summary of the commands available to the user to control the execution of the simulation. After Chapter 2, Chapters 6 and 7 are of formeost importance to the new application developer.

The display of detector geometry, tracks and events may be incorporated into a simulation application by using the tools described in **Chapter 8, "Visualization"**.

Chapter 9, "Examples" provides a set of novice and advanced simulation codes which may be compiled and run "as is" from the Geant4 source code. These examples may be used as educational tools or as base code from which more complex applications are developed.

Chapter 2. Getting Started with Geant4 - Running a Simple Example

2.1. How to Define the main() Program

2.1.1. A Sample `main()` Method

The contents of `main()` will vary according to the needs of a given simulation application and therefore must be supplied by the user. The Geant4 toolkit does not provide a `main()` method, but a sample is provided here as a guide to the beginning user. Example 2.1 is the simplest example of `main()` required to build a simulation program.

Example 2.1. Simplest example of `main()`

```
#include "G4RunManager.hh"
#include "G4UImanager.hh"

#include "ExN01DetectorConstruction.hh"
#include "ExN01PhysicsList.hh"
#include "ExN01PrimaryGeneratorAction.hh"

int main()
{
  // construct the default run manager
  G4RunManager* runManager = new G4RunManager;

  // set mandatory initialization classes
  runManager->SetUserInitialization(new ExN01DetectorConstruction);
  runManager->SetUserInitialization(new ExN01PhysicsList);

  // set mandatory user action class
  runManager->SetUserAction(new ExN01PrimaryGeneratorAction);

  // initialize G4 kernel
  runManager->Initialize();

  // get the pointer to the UI manager and set verbosities
  G4UImanager* UI = G4UImanager::GetUIpointer();
  UI->ApplyCommand("/run/verbose 1");
  UI->ApplyCommand("/event/verbose 1");
  UI->ApplyCommand("/tracking/verbose 1");

  // start a run
  int numberOfEvent = 3;
  runManager->BeamOn(numberOfEvent);

  // job termination
  delete runManager;
  return 0;
}
```

The `main()` method is implemented by two toolkit classes, *G4RunManager* and *G4UImanager*, and three classes, *ExN01DetectorConstruction*, *ExN01PhysicsList* and *ExN01PrimaryGeneratorAction*, which are derived from toolkit classes. Each of these are explained in the following sections.

2.1.2. *G4RunManager*

The first thing `main()` must do is create an instance of the *G4RunManager* class. This is the only manager class in the Geant4 kernel which should be explicitly constructed in the user's `main()`. It controls the flow of the program and manages the event loop(s) within a run. When *G4RunManager* is created, the other major manager classes are also created. They are deleted automatically when *G4RunManager* is deleted. The run manager is also responsible for managing initialization procedures, including methods in the user initialization classes. Through these the run manager must be given all the information necessary to build and run the simulation, including

1. how the detector should be constructed,
2. all the particles and all the physics processes to be simulated,
3. how the primary particle(s) in an event should be produced and
4. any additional requirements of the simulation.

In the sample `main()` the lines

```
runManager->SetUserInitialization(new ExN01DetectorConstruction);
runManager->SetUserInitialization(new ExN01PhysicsList);
```

create objects which specify the detector geometry and physics processes, respectively, and pass their pointers to the run manager. *ExN01DetectorConstruction* is an example of a user initialization class which is derived from *G4VUserDetectorConstruction*. This is where the user describes the entire detector setup, including

- its geometry,
- the materials used in its construction,
- a definition of its sensitive regions and
- the readout schemes of the sensitive regions.

Similarly *ExN01PhysicsList* is derived from *G4VUserPhysicsList* and requires the user to define

- the particles to be used in the simulation,
- the range cuts for these particles and
- all the physics processes to be simulated.

The next instruction in `main()`

```
runManager->SetUserAction(new ExN01PrimaryGeneratorAction);
```

creates an instance of a particle generator and passes its pointer to the run manager. *ExN01PrimaryGeneratorAction* is an example of a user action class which is derived from *G4VUserPrimaryGeneratorAction*. In this class the user must describe the initial state of the primary event. This class has a public virtual method named `generatePrimaries()` which will be invoked at the beginning of each event. Details will be given in Section 2.6. Note that Geant4 does not provide any default behavior for generating a primary event.

The next instruction

```
runManager->Initialize();
```

performs the detector construction, creates the physics processes, calculates cross sections and otherwise sets up the run. The final run manager method in `main()`

```
int numberOfEvent = 3;
runManager->beamOn(numberOfEvent);
```

begins a run of three sequentially processed events. The `beamOn()` method may be invoked any number of times within `main()` with each invocation representing a separate run. Once a run has begun neither the detector setup nor the physics processes may be changed. They may be changed between runs, however, as described in Section 3.4.4. More information on *G4RunManager* in general is found in Section 3.4.

As mentioned above, other manager classes are created when the run manager is created. One of these is the user interface manager, *G4UImanager*. In `main()` a pointer to the interface manager must be obtained

```
G4UImanager* UI = G4UImanager::getUIpointer();
```

in order for the user to issue commands to the program. In the present example the `applyCommand()` method is called three times to direct the program to print out information at the run, event and tracking levels of simulation. A wide range of commands is available which allows the user detailed control of the simulation. A list of these commands can be found in Section 7.1.

2.1.3. User Initialization and Action Classes

2.1.3.1. Mandatory User Classes

There are three classes which must be defined by the user. Two of them are user initialization classes, and the other is a user action class. They must be derived from the abstract base classes provided by Geant4: *G4VUserDetectorConstruction*, *G4VuserPhysicsList* and *G4VuserPrimaryGeneratorAction*. Geant4 does not provide default behavior for these classes. *G4RunManager* checks for the existence of these mandatory classes when the `Initialize()` and `BeamOn()` methods are invoked.

As mentioned in the previous section, *G4VUserDetectorConstruction* requires the user to define the detector and *G4VUserPhysicsList* requires the user to define the physics. Detector definition will be discussed in Sections

Section 2.2 and Section 2.3. Physics definition will be discussed in Sections Section 2.4 and Section 2.5. The user action *G4VuserPrimaryGeneratorAction* requires that the initial event state be defined. Primary event generation will be discussed in Section 2.7.

2.1.3.2. Optional User Action Classes

Geant4 provides five user hook classes:

- *G4UserRunAction*
- *G4UserEventAction*
- *G4UserStackingAction*
- *G4UserTrackingAction*
- *G4UserSteppingAction*

There are several virtual methods in each of these classes which allow the specification of additional procedures at all levels of the simulation application. Details of the user initialization and action classes are provided in Chapter 6.

2.1.4. *G4UImanager* and UI CommandSubmission

Geant4 provides a category named **intercoms**. *G4UImanager* is the manager class of this category. Using the functionalities of this category, you can invoke **set** methods of class objects of which you do not know the pointer. In Example 2.2, the verbosities of various Geant4 manager classes are set. Detailed mechanism description and usage of **intercoms** will be given in the next chapter, with a list of available commands. Command submission can be done all through the application.

Example 2.2. An example of `main()` using interactive terminal and visualization. Code modified from the previous example are shown in *blue*.

```
#include "G4RunManager.hh"
#include "G4UImanager.hh"
#include "G4UIExecutive.hh"
#include "G4VisExecutive.hh"

#include "N02DetectorConstruction.hh"
#include "N02PhysicsList.hh"
#include "N02PrimaryGeneratorAction.hh"
#include "N02RunAction.hh"
#include "N02EventAction.hh"
#include "N02SteppingAction.hh"

#include "g4templates.hh"

int main(int argc,char** argv)
{
  // construct the default run manager
  G4RunManager * runManager = new G4RunManager;

  // set mandatory initialization classes
  N02DetectorConstruction* detector = new N02DetectorConstruction;
  runManager->SetUserInitialization(detector);
  runManager->SetUserInitialization(new N02PhysicsList);

  // visualization manager
  G4VisManager* visManager = new G4VisExecutive;
  visManager->Initialize();

  // set user action classes
  runManager->SetUserAction(new N02PrimaryGeneratorAction(detector));
  runManager->SetUserAction(new N02RunAction);
  runManager->SetUserAction(new N02EventAction);
  runManager->SetUserAction(new N02SteppingAction);

  // get the pointer to the User Interface manager
  G4UImanager* UImanager = G4UImanager::GetUIpointer();


  if(argc==1)
  // Define (G)UI terminal for interactive mode
  {
    G4UIExecutive * ui = new G4UIExecutive(argc,argv);
    UImanager->ApplyCommand("/control/execute prerun.g4mac");
    ui->sessionStart();
    delete ui;
  }
  else
  // Batch mode
  {
    G4String command = "/control/execute ";
    G4String fileName = argv[1];
    UImanager->ApplyCommand(command+fileName);
  }


  // job termination
  delete visManager;
  delete runManager;

  return 0;
}
```

2.1.5. *G4cout* and *G4cerr*

Although not yet included in the above examples, output streams will be needed. *G4cout* and *G4cerr* are **iostream** objects defined by Geant4. The usage of these objects is exactly the same as the ordinary *cout* and *cerr*, except that the output streams will be handled by *G4UImanager*. Thus, output strings may be displayed on another window or stored in a file. Manipulation of these output streams will be described in Section 7.2.4. These objects should be used instead of the ordinary *cout* and *cerr*.

2.2. How to Define a Detector Geometry

2.2.1. Basic Concepts

A detector geometry in Geant4 is made of a number of volumes. The largest volume is called the **World** volume. It must contain, with some margin, all other volumes in the detector geometry. The other volumes are created and placed inside previous volumes, included in the World volume. The most simple (and efficient) shape to describe the World is a box.

Each volume is created by describing its shape and its physical characteristics, and then placing it inside a containing volume.

When a volume is placed within another volume, we call the former volume the daughter volume and the latter the mother volume. The coordinate system used to specify where the daughter volume is placed, is the coordinate system of the mother volume.

To describe a volume's shape, we use the concept of a solid. A solid is a geometrical object that has a shape and specific values for each of that shape's dimensions. A cube with a side of 10 centimeters and a cylinder of radius 30 cm and length 75 cm are examples of solids.

To describe a volume's full properties, we use a logical volume. It includes the geometrical properties of the solid, and adds physical characteristics: the material of the volume; whether it contains any sensitive detector elements; the magnetic field; etc.

We have yet to describe how to position the volume. To do this you create a physical volume, which places a copy of the logical volume inside a larger, containing, volume.

2.2.2. Create a Simple Volume

What do you need to do to create a volume?

- Create a solid.
- Create a logical volume, using this solid, and adding other attributes.

2.2.3. Choose a Solid

To create a simple box, you only need to define its name and its extent along each of the Cartesian axes. You can find an example how to do this in Novice Example N01.

In the detector description in the source file `ExN01DetectorConstruction.cc`, you will find the following box definition:

Example 2.3. Creating a box.

```
G4double expHall_x = 3.0*m;
G4double expHall_y = 1.0*m;
G4double expHall_z = 1.0*m;

G4Box* experimentalHall_box
   = new G4Box("expHall_box",expHall_x,expHall_y,expHall_z);
```

This creates a box named "expHall_box" with extent from -3.0 meters to +3.0 meters along the X axis, from -1.0 to 1.0 meters in Y, and from -1.0 to 1.0 meters in Z.

It is also very simple to create a cylinder. To do this, you can use the *G4Tubs* class.

Example 2.4. Creating a cylinder.

```
G4double innerRadiusOfTheTube = 0.*cm;
G4double outerRadiusOfTheTube = 60.*cm;
G4double hightOfTheTube = 25.*cm;
G4double startAngleOfTheTube = 0.*deg;
G4double spanningAngleOfTheTube = 360.*deg;

G4Tubs* tracker_tube
  = new G4Tubs("tracker_tube",
               innerRadiusOfTheTube,
               outerRadiusOfTheTube,
               hightOfTheTube,
               startAngleOfTheTube,
               spanningAngleOfTheTube);
```

This creates a full cylinder, named "tracker_tube", of radius 60 centimeters and length 50 cm.

2.2.4. Create a Logical Volume

To create a logical volume, you must start with a solid and a material. So, using the box created above, you can create a simple logical volume filled with argon gas (see materials) by entering:

```
G4LogicalVolume* experimentalHall_log
   = new G4LogicalVolume(experimentalHall_box,Ar,"expHall_log");
```

This logical volume is named "expHall_log".

Similarly we create a logical volume with the cylindrical solid filled with aluminium

```
G4LogicalVolume* tracker_log
  = new G4LogicalVolume(tracker_tube,Al,"tracker_log");
```

and named "tracker_log"

2.2.5. Place a Volume

How do you place a volume? You start with a logical volume, and then you decide the already existing volume inside of which to place it. Then you decide where to place its center within that volume, and how to rotate it. Once you have made these decisions, you can create a physical volume, which is the placed instance of the volume, and embodies all of these atributes.

2.2.6. Create a Physical Volume

You create a physical volume starting with your logical volume. A physical volume is simply a placed instance of the logical volume. This instance must be placed inside a mother logical volume. For simplicity it is unrotated:

Example 2.5. A simple physical volume.

```
G4double trackerPos_x = -1.0*meter;
G4double trackerPos_y =  0.0*meter;
G4double trackerPos_z =  0.0*meter;

G4VPhysicalVolume* tracker_phys
  = new G4PVPlacement(0,                       // no rotation
                      G4ThreeVector(trackerPos_x,trackerPos_y,trackerPos_z),
                                               // translation position
                      tracker_log,             // its logical volume
                      "tracker",               // its name
                      experimentalHall_log,    // its mother (logical) volume
                      false,                   // no boolean operations
                      0);                      // its copy number
```

This places the logical volume `tracker_log` at the origin of the mother volume `experimentalHall_log`, shifted by one meter along X and unrotated. The resulting physical volume is named "tracker" and has a copy number of 0.

An exception exists to the rule that a physical volume must be placed inside a mother volume. That exception is for the World volume, which is the largest volume created, and which contains all other volumes. This volume obviously cannot be contained in any other. Instead, it must be created as a *G4PVPlacement* with a null mother pointer. It also must be unrotated, and it must be placed at the origin of the global coordinate system.

Generally, it is best to choose a simple solid as the World volume, and in Example N01, we use the experimental hall:

Example 2.6. The World volume from Example N01.

```
G4VPhysicalVolume* experimentalHall_phys
    = new G4PVPlacement(0,                       // no rotation
                        G4ThreeVector(0.,0.,0.), // translation position
                        experimentalHall_log,    // its logical volume
                        "expHall",               // its name
                        0,                       // its mother volume
                        false,                   // no boolean operations
                        0);                      // its copy number
```

2.2.7. Coordinate Systems and Rotations

In Geant4, the rotation matrix associated to a placed physical volume represents the rotation of the reference system of this volume with respect to its mother.

A rotation matrix is normally constructed as in CLHEP, by instantiating the identity matrix and then applying a rotation to it. This is also demonstrated in Example N04.

2.3. How to Specify Materials in the Detector

2.3.1. General Considerations

In nature, general materials (chemical compounds, mixtures) are made of elements, and elements are made of isotopes. Therefore, these are the three main classes designed in Geant4. Each of these classes has a table as a static data member, which is for keeping track of the instances created of the respective classes.

The *G4Element* class describes the properties of the atoms:

- atomic number,
- number of nucleons,
- atomic mass,
- shell energy,
- as well as quantities such as cross sections per atom, etc.

The *G4Material* class describes the macroscopic properties of matter:

- density,
- state,
- temperature,
- pressure,
- as well as macroscopic quantities like radiation length, mean free path, dE/dx, etc.

The *G4Material* class is the one which is visible to the rest of the toolkit, and is used by the tracking, the geometry, and the physics. It contains all the information relative to the eventual elements and isotopes of which it is made, at the same time hiding the implementation details.

2.3.2. Define a Simple Material

In the example below, liquid argon is created, by specifying its name, density, mass per mole, and atomic number.

Example 2.7. Creating liquid argon.

```
G4double density = 1.390*g/cm3;
G4double a = 39.95*g/mole;
G4Material* lAr = new G4Material(name="liquidArgon", z=18., a, density);
```

The pointer to the material, *lAr*, will be used to specify the matter of which a given logical volume is made:

```
G4LogicalVolume* myLbox = new G4LogicalVolume(aBox,lAr,"Lbox",0,0,0);
```

2.3.3. Define a Molecule

In the example below, the water, *H2O*, is built from its components, by specifying the number of atoms in the molecule.

Example 2.8. Creating water by defining its molecular components.

```
a = 1.01*g/mole;
G4Element* elH  = new G4Element(name="Hydrogen",symbol="H" , z= 1., a);

a = 16.00*g/mole;
G4Element* elO  = new G4Element(name="Oxygen"  ,symbol="O" , z= 8., a);

density = 1.000*g/cm3;
G4Material* H2O = new G4Material(name="Water",density,ncomponents=2);
H2O->AddElement(elH, natoms=2);
H2O->AddElement(elO, natoms=1);
```

2.3.4. Define a Mixture by Fractional Mass

In the example below, air is built from nitrogen and oxygen, by giving the fractional mass of each component.

Example 2.9. Creating air by defining the fractional mass of its components.

```
a = 14.01*g/mole;
G4Element* elN  = new G4Element(name="Nitrogen",symbol="N" , z= 7., a);

a = 16.00*g/mole;
G4Element* elO  = new G4Element(name="Oxygen"  ,symbol="O" , z= 8., a);

density = 1.290*mg/cm3;
G4Material* Air = new G4Material(name="Air  ",density,ncomponents=2);
Air->AddElement(elN, fractionmass=70*perCent);
Air->AddElement(elO, fractionmass=30*perCent);
```

2.3.5. Define a Material from the Geant4 Material Database

In the example below, air and water are accessed via the Geant4 material database.

Example 2.10. Defining air and water from the internal Geant4 database.

```
G4NistManager* man = G4NistManager::Instance();

G4Material* H2O  = man->FindOrBuildMaterial("G4_WATER");
G4Material* Air  = man->FindOrBuildMaterial("G4_AIR");
```

2.3.6. Print Material Information

Example 2.11. Printing information about materials.

```
G4cout << H2O;                                \\ print a given material
G4cout << *(G4Material::GetMaterialTable());  \\ print the list of materials
```

In `examples/novice/N03/N03DetectorConstruction.cc`, you will find examples of all possible ways to build a material.

2.4. How to Specify Particles

`G4VuserPhysicsList` is one of the mandatory user base classes described in Section 2.1. Within this class all particles and physics processes to be used in your simulation must be defined. The range cut-off parameter should also be defined in this class.

The user must create a class derived from `G4VuserPhysicsList` and implement the following pure virtual methods:

```
ConstructParticle();      // construction of particles
ConstructProcess();       // construct processes and register them to particles
SetCuts();                // setting a range cut value for all particles
```

This section provides some simple examples of the `ConstructParticle()` and `SetCuts()` methods. For information on `ConstructProcess()` methods, please see Section 2.5.

2.4.1. Particle Definition

Geant4 provides various types of particles for use in simulations:

- ordinary particles, such as electrons, protons, and gammas
- resonant particles with very short lifetimes, such as vector mesons and delta baryons
- nuclei, such as deuteron, alpha, and heavy ions (including hyper-nuclei)
- quarks, di-quarks, and gluon

Each particle is represented by its own class, which is derived from `G4ParticleDefinition`. (Exception: G4Ions represents all heavy nuclei. Please see Section 5.3.) Particles are organized into six major categories:

- lepton,
- meson,
- baryon,
- boson,
- shortlived and
- ion,

each of which is defined in a corresponding sub-directory under `geant4/source/particles`. There is also a corresponding granular library for each particle category.

2.4.1.1. The `G4ParticleDefinition` Class

`G4ParticleDefinition` has properties which characterize individual particles, such as, name, mass, charge, spin, and so on. Most of these properties are "read-only" and can not be changed directly. `G4ParticlePropertyTable` is used to retrieve (load) particle property of `G4ParticleDefinition` into (from) `G4ParticlePropertyData`.

2.4.1.2. How to Access a Particle

Each particle class type represents an individual particle type, and each class has a single object. This object can be accessed by using the static method of each class. There are some exceptions to this rule; please see Section 5.3 for details.

For example, the class `G4Electron` represents the electron and the member `G4Electron::theInstance` points its only object. The pointer to this object is available through the static methods `G4Electron::ElectronDefinition()`. `G4Electron::Definition()`.

More than 100 types of particles are provided by default, to be used in various physics processes. In normal applications, users will not need to define their own particles.

The unique object for each particle class is created when its static method to get the pointer is called at the first time. Because particles are dynamic objects and should be instantiated before initialization of physics processes, you must explicitly invoke static methods of all particle classes required by your program at the initialization step. (NOTE: The particle object was static and created automatically before 8.0 release)

2.4.1.3. Dictionary of Particles

The `G4ParticleTable` class is provided as a dictionary of particles. Various utility methods are provided, such as:

```
FindParticle(G4String name);         // find the particle by name
FindParticle(G4int PDGencoding)      // find the particle by PDG encoding .
```

`G4ParticleTable` is defined as a singleton object, and the static method `G4ParticleTable::GetParticleTable()` provides its pointer.

As for heavy ions (including hyper-nuclei), objects are created dynamically by requests from users and processes. The `G4ParticleTable` class provides methods to create ions, such as:

```
G4ParticleDefinition* GetIon(  G4int    atomicNumber,
                               G4int    atomicMass,
                               G4double   excitationEnergy);
```

Particles are registered automatically during construction. The user has no control over particle registration.

2.4.1.4. Constructing Particles

`ConstructParticle()` is a pure virtual method, in which the static member functions for all the particles you require should be called. This ensures that objects of these particles are created.

WARNING: You must define "All PARTICLE TYPES" which are used in your application, except for heavy ions. "All PARTICLE TYPES" means not only primary particles, but also all other particles which may appear as secondaries generated by physics processes you use. Beginning with Geant4 version 8.0, you should keep this rule strictly because all particle definitions are revised to "non-static" objects.

For example, suppose you need a proton and a geantino, which is a virtual particle used for simulation and which does not interact with materials. The `ConstructParticle()` method is implemented as below:

Example 2.12. Construct a proton and a geantino.

```
void ExN01PhysicsList::ConstructParticle()
{
  G4Proton::ProtonDefinition();
  G4Geantino::GeantinoDefinition();
}
```

Due to the large number of pre-defined particles in Geant4, it is cumbersome to list all the particles by this method. If you want all the particles in a Geant4 particle category, there are six utility classes, corresponding to each of the particle categories, which perform this function:

- `G4BosonConstructor`
- `G4LeptonConstructor`
- `G4MesonConstructor`
- `G4BarionConstructor`
- `G4IonConstructor`
- `G4ShortlivedConstructor`.

An example of this is shown in `ExN05PhysicsList`, listed below.

Example 2.13. Construct all leptons.

```
void ExN05PhysicsList::ConstructLeptons()
{
  // Construct all leptons
  G4LeptonConstructor pConstructor;
  pConstructor.ConstructParticle();
}
```

2.4.2. Range Cuts

To avoid infrared divergence, some electromagnetic processes require a threshold below which no secondary will be generated. Because of this requirement, gammas, electrons and positrons require production thresholds which the user should define. This threshold should be defined as a distance, or range cut-off, which is internally converted to an energy for individual materials. The range threshold should be defined in the initialization phase using the `SetCuts()` method of `G4VUserPhysicsList`. Section 5.5 discusses threshold and tracking cuts in detail.

2.4.2.1. Setting the cuts

Production threshold values should be defined in `SetCuts()` which is a pure virtual method of the `G4VUserPhysicsList` class. Construction of particles, materials, and processes should precede the invocation of `SetCuts()`. `G4RunManager` takes care of this sequence in usual applications.

This range cut value is converted threshold energies for each material and for each particle type (i.e. electron, positron and gamma) so that the particle with threshold energy stops (or is absorbed) after traveling the range cut distance. In addition, from the 9.3 release ,this range cut value is applied to the proton as production thresholds of nuclei for hadron elastic processes. In this case, the range cut value does not means the distance of traveling. Threshold energies are calculated by a simple formula from the cut in range.

Note that the upper limit of the threshold energy is defined as 10 GeV. If you want to set higher threshold energy, you can change the limit by using "/cuts/setMaxCutEnergy" command before setting the range cut.

The idea of a "unique cut value in range" is one of the important features of Geant4 and is used to handle cut values in a coherent manner. For most applications, users need to determine only one cut value in range, and apply this value to gammas, electrons and positrons alike. (and proton too)

In such case, the `SetCutsWithDefault()` method may be used. It is provided by the `G4VuserPhysicsList` base class, which has a `defaultCutValue` member as the default range cut-off value. `SetCutsWithDefault()` uses this value.

It is possible to set different range cut values for gammas, electrons and positrons, and also to set different range cut values for each geometrical region. In such cases however, one must be careful with physics outputs because Geant4 processes (especially energy loss) are designed to conform to the "unique cut value in range" scheme.

Example 2.14. Set cut values by using the default cut value.

```
void ExN04PhysicsList::SetCuts()
{
  //   the G4VUserPhysicsList::SetCutsWithDefault() method sets
  //   the default cut value for all particle types
  SetCutsWithDefault();
}
```

The `defaultCutValue` is set to 1.0 mm by default. Of course, you can set the new default cut value in the constructor of your physics list class as shown below.

Example 2.15. Set the default cut value.

```
ExN04PhysicsList::ExN04PhysicsList():  G4VUserPhysicsList()
{
  // default cut value  (1.0mm)
  defaultCutValue = 1.0*mm;
}
```

The `SetDefaultCutValue()` method in `G4VUserPhysicsList` may also be used, and the "/run/setCut" command may be used to change the default cut value interactively.

You can set different cut values in range for different particle types. The "/run/setCutForAGivenParticle" command may be used interactively.

WARNING: DO NOT change cut values inside the event loop. Cut values may however be changed between runs.

An example implementation of `SetCuts()` is shown below:

Example 2.16. Example implementation of the `SetCuts()` method.

```
void ExN03PhysicsList::SetCuts()
{
  // set cut values for gamma at first and for e- second and next for e+,
  // because some processes for e+/e- need cut values for gamma
  SetCutValue(cutForGamma, "gamma");
  SetCutValue(cutForElectron, "e-");
  SetCutValue(cutForElectron, "e+");
  SetCutValue(cutForProton,   "proton");
}
```

Beginning with Geant4 version 5.1, it is now possible to set production thresholds for each geometrical region. This new functionality is described in Section 5.5.

2.5. How to Specify Physics Processes

2.5.1. Physics Processes

Physics processes describe how particles interact with materials. Geant4 provides seven major categories of processes:

- electromagnetic,
- hadronic,
- transportation,
- decay,
- optical,
- photolepton_hadron, and
- parameterisation.

All physics processes are derived from the *G4VProcess* base class. Its virtual methods

- `AtRestDoIt`,
- `AlongStepDoIt`, and
- `PostStepDoIt`

and the corresponding methods

- `AtRestGetPhysicalInteractionLength`,
- `AlongStepGetPhysicalInteractionLength`, and
- `PostStepGetPhysicalInteractionLength`

describe the behavior of a physics process when they are implemented in a derived class. The details of these methods are described in Section 5.2.

The following are specialized base classes to be used for simple processes:

G4VAtRestProcess
: Processes with only `AtRestDoIt`

G4VContinuousProcess
Processes with only `AlongStepDoIt`

G4VDiscreteProcess
processes with only `PostStepDoIt`

Another 4 virtual classes, such as *G4VContinuousDiscreteProcess*, are provided for complex processes.

2.5.2. Managing Processes

The *G4ProcessManager* class contains a list of processes that a particle can undertake. It has information on the order of invocation of the processes, as well as which kind of `DoIt` method is valid for each process in the list. A *G4ProcessManager* object corresponds to each particle and is attached to the *G4ParticleDefiniton* class.

In order to validate processes, they should be registered with the particle's *G4ProcessManager*. Process ordering information is included by using the `AddProcess()` and `SetProcessOrdering()` methods. For registration of simple processes, the `AddAtRestProcess()`, `AddContinuousProcess()` and `AddDiscreteProcess()` methods may be used.

G4ProcessManager is able to turn some processes on or off during a run by using the `ActivateProcess()` and `InActivateProcess()` methods. These methods are valid only after process registration is complete, so they must not be used in the *PreInit* phase.

The *G4VUserPhysicsList* class creates and attaches *G4ProcessManager* objects to all particle classes defined in the `ConstructParticle()` method.

2.5.3. Specifying Physics Processes

G4VUserPhysicsList is the base class for a "mandatory user class" (see Section 2.1), in which all physics processes and all particles required in a simulation must be registered. The user must create a class derived from *G4VUserPhysicsList* and implement the pure virtual method `ConstructProcess()`.

For example, if just the *G4Geantino* particle class is required, only the transportation process need be registered. The `ConstructProcess()` method would then be implemented as follows:

Example 2.17. Register processes for a geantino.

```
void ExN01PhysicsList::ConstructProcess()
{
  // Define transportation process
  AddTransportation();
}
```

Here, the `AddTransportation()` method is provided in the *G4VUserPhysicsList* class to register the *G4Transportation* class with all particle classes. The *G4Transportation* class (and/or related classes) describes the particle motion in space and time. It is the mandatory process for tracking particles.

In the `ConstructProcess()` method, physics processes should be created and registered with each particle's instance of *G4ProcessManager*.

An example of process registration is given in the *G4VUserPhysicsList*::`AddTransportation()` method.

Registration in *G4ProcessManager* is a complex procedure for other processes and particles because the relations between processes are crucial for some processes. Please see Section 5.2 and the example codes.

An example of electromagnetic process registration for photons is shown below:

Example 2.18. Register processes for a gamma.

```
void MyPhysicsList::ConstructProcess()
{
  // Define transportation process
  AddTransportation();
  // electromagnetic processes
  ConstructEM();
}
void MyPhysicsList::ConstructEM()
{
   //  Get the process manager for gamma
  G4ParticleDefinition* particle = G4Gamma::GammaDefinition();
  G4ProcessManager* pmanager = particle->GetProcessManager();

  // Construct processes for gamma
  G4PhotoElectricEffect * thePhotoElectricEffect = new G4PhotoElectricEffect();
  G4ComptonScattering * theComptonScattering = new G4ComptonScattering();
  G4GammaConversion* theGammaConversion = new G4GammaConversion();

  // Register processes to gamma's process manager
  pmanager->AddDiscreteProcess(thePhotoElectricEffect);
  pmanager->AddDiscreteProcess(theComptonScattering);
  pmanager->AddDiscreteProcess(theGammaConversion);
}
```

2.6. How to Generate a Primary Event

2.6.1. Generating Primary Events

G4VuserPrimaryGeneratorAction is one of the mandatory classes available for deriving your own concrete class. In your concrete class, you have to specify how a primary event should be generated. Actual generation of primary particles will be done by concrete classes of *G4VPrimaryGenerator*, explained in the following sub-section. Your *G4VUserPrimaryGeneratorAction* concrete class just arranges the way primary particles are generated.

Example 2.19. An example of a *G4VUserPrimaryGeneratorAction* concrete class using *G4ParticleGun*. For the usage of *G4ParticleGun* refer to the next subsection.

```
#ifndef ExN01PrimaryGeneratorAction_h
#define ExN01PrimaryGeneratorAction_h 1

#include "G4VUserPrimaryGeneratorAction.hh"

class G4ParticleGun;
class G4Event;

class ExN01PrimaryGeneratorAction : public G4VUserPrimaryGeneratorAction
{
  public:
    ExN01PrimaryGeneratorAction();
    ~ExN01PrimaryGeneratorAction();

  public:
    void generatePrimaries(G4Event* anEvent);

  private:
    G4ParticleGun* particleGun;
};

#endif

#include "ExN01PrimaryGeneratorAction.hh"
#include "G4Event.hh"
#include "G4ParticleGun.hh"
#include "G4ThreeVector.hh"
#include "G4Geantino.hh"
#include "globals.hh"

ExN01PrimaryGeneratorAction::ExN01PrimaryGeneratorAction()
{
  G4int n_particle = 1;
  particleGun = new G4ParticleGun(n_particle);

  particleGun->SetParticleDefinition(G4Geantino::GeantinoDefinition());
  particleGun->SetParticleEnergy(1.0*GeV);
  particleGun->SetParticlePosition(G4ThreeVector(-2.0*m,0.0*m,0.0*m));
}

ExN01PrimaryGeneratorAction::~ExN01PrimaryGeneratorAction()
{
  delete particleGun;
}

void ExN01PrimaryGeneratorAction::generatePrimaries(G4Event* anEvent)
{
  G4int i = anEvent->get_eventID() % 3;
  switch(i)
  {
    case 0:
      particleGun->SetParticleMomentumDirection(G4ThreeVector(1.0,0.0,0.0));
      break;
    case 1:
      particleGun->SetParticleMomentumDirection(G4ThreeVector(1.0,0.1,0.0));
      break;
    case 2:
      particleGun->SetParticleMomentumDirection(G4ThreeVector(1.0,0.0,0.1));
      break;
  }

  particleGun->generatePrimaryVertex(anEvent);
}
```

2.6.1.1. Selection of the generator

In the constructor of your *G4VUserPrimaryGeneratorAction*, you should instantiate the primary generator(s). If necessary, you need to set some initial conditions for the generator(s).

In Example 2.19, *G4ParticleGun* is constructed to use as the actual primary particle generator. Methods of *G4ParticleGun* are described in the following section. Please note that the primary generator object(s) you construct in your *G4VUserPrimaryGeneratorAction* concrete class must be deleted in your destructor.

2.6.1.2. Generation of an event

G4VUserPrimaryGeneratorAction has a pure virtual method named `generatePrimaries()`. This method is invoked at the beginning of each event. In this method, you have to invoke the *G4VPrimaryGenerator* concrete class you instantiated via the `generatePrimaryVertex()` method.

You can invoke more than one generator and/or invoke one generator more than once. Mixing up several generators can produce a more complicated primary event.

2.6.2. G4VPrimaryGenerator

Geant4 provides three *G4VPrimaryGenerator* concrete classes. Among these *G4ParticleGun* and *G4GeneralParticleSource* will be discussed here. The third one is *G4HEPEvtInterface*, which will be discussed in Section 3.6.

2.6.2.1. G4ParticleGun

G4ParticleGun is a generator provided by Geant4. This class generates primary particle(s) with a given momentum and position. It does not provide any sort of randomizing. The constructor of *G4ParticleGun* takes an integer which causes the generation of one or more primaries of exactly same kinematics. It is a rather frequent user requirement to generate a primary with randomized energy, momentum, and/or position. Such randomization can be achieved by invoking various set methods provided by *G4ParticleGun*. The invocation of these methods should be implemented in the `generatePrimaries()` method of your concrete *G4VUserPrimaryGeneratorAction* class before invoking `generatePrimaryVertex()` of *G4ParticleGun*. Geant4 provides various random number generation methods with various distributions (see Section 3.2).

2.6.2.2. Public methods of *G4ParticleGun*

The following methods are provided by *G4ParticleGun*, and all of them can be invoked from the `generatePrimaries()` method in your concrete *G4VUserPrimaryGeneratorAction* class.

- `void SetParticleDefinition(G4ParticleDefinition*)`
- `void SetParticleMomentum(G4ParticleMomentum)`
- `void SetParticleMomentumDirection(G4ThreeVector)`
- `void SetParticleEnergy(G4double)`
- `void SetParticleTime(G4double)`
- `void SetParticlePosition(G4ThreeVector)`
- `void SetParticlePolarization(G4ThreeVector)`
- `void SetNumberOfParticles(G4int)`

2.6.2.3. G4GeneralParticleSource

For many applications `G4ParticleGun` is a suitable particle generator. Howevr if you want to generate primary particles in more sophisticated manner, you can utilize `G4GeneralParticleSource` - Geant4 General Particle Source module (GPS).

Using this tool, you can control the following characteristics of primary particles:

- Spectrum: linear, exponential, power-law, Gaussian, blackbody, or piece-wise fits to data.
- Angular distribution: unidirectional, isotropic, cosine-law, beam or arbitrary (user defined).
- Spatial sampling: on simple 2D or 3D surfaces such as discs, spheres, and boxes.
- Multiple sources: multiple independent sources can be used in the same run.

Details of information on the General Source Particle Module can be found in the documents Geant4 General Particle Source.

2.7. How to Make an Executable Program

2.7.1. Building ExampleN01 in a UNIX Environment

The code for the user examples in Geant4 is placed in the directory `$G4INSTALL/examples`, where `$G4INSTALL` is the environment variable set to the place where the Geant4 distribution is installed (set by default to `$HOME/geant4`). In the following sections, a quick overview on how the GNUmake mechanism works in Geant4 will be given, and we will show how to build a concrete example, "ExampleN01", which is part of the Geant4 distribution.

2.7.1.1. How GNUmake works in Geant4

The GNUmake process in Geant4 is mainly controlled by the following GNUmake script files (`*.gmk` scripts are placed in `$G4INSTALL/config`):

`architecture.gmk`
: invoking and defining all the architecture specific settings and paths which are stored in `$G4INSTALL/config/sys`.

`common.gmk`
: defining all general GNUmake rules for building objects and libraries

`globlib.gmk`
: defining all general GNUmake rules for building compound libraries

`binmake.gmk`
: defining the general GNUmake rules for building executables

`GNUmakefile`
: placed inside each directory in the Geant4 distribution and defining directives specific to build a library, a set of sub-libraries, or an executable.

Kernel libraries are placed by default in `$G4INSTALL/lib/$G4SYSTEM`, where `$G4SYSTEM` specifies the system architecture and compiler in use. Executable binaries are placed in `$G4WORKDIR/bin/$G4SYSTEM`, and temporary files (object-files and data products of the compilation process) in `$G4WORKDIR/tmp/$G4SYSTEM`. `$G4WORKDIR` (set by default to `$G4INSTALL`) should be set by the user to specify the place his/her own workdir for Geant4 in the user area.

For more information on how to build Geant4 kernel libraries and set up the correct environment for Geant4, refer to the "Installation Guide".

2.7.1.2. Building the executable

The compilation process to build an executable, such as an example from `$G4INSTALL/examples`, is started by invoking the "make" command from the (sub)directory in which you are interested. To build, for instance, exampleN01 in your `$G4WORKDIR` area, you should copy the module `$G4INSTALL/examples` to your `$G4WORKDIR` and do the following actions:

```
> cd $G4WORKDIR/examples/novice/N01
> gmake
```

This will create, in `$G4WORKDIR/bin/$G4SYSTEM`, the "exampleN01" executable, which you can invoke and run. You should actually add `$G4WORKDIR/bin/$G4SYSTEM` to `$PATH` in your environment.

2.7.2. Building ExampleN01 in a Windows Environment

The procedure to build a Geant4 executable on a system based on a Windows system is similar to what should be done on a UNIX based system, assuming that your system is equipped with GNUmake, MS-Visual C++ compiler and the required software to run Geant4 (see "Installation Guide").

2.7.2.1. Building the executable

See paragraph Section 2.7.1.

2.8. How to Set Up an Interactive Session

2.8.1. Introduction

2.8.1.1. Roles of the "intercoms" category

The "intercoms" category provides an expandable command interpreter. It is the key mechanism of Geant4 to realize secure user interactions in all categories without being annoyed by the dependencies among categories. The Geant4 commands can be used both in a interactive terminal session and in a batch mode with a maco file or a direct C++ call.

2.8.1.2. User Interfaces to steer the simulation

Geant4 can be controllled by a seriese of Geant4 UI commands. The "intercoms" category provides the abstract class *G4UIsession* that processes interactive commands. The concrete implementation of (graphical) user interfaceis is located in the "interfaces" category. This interfacing strategy opens an important door towards various user interface tools, and allows Geant4 to utilize the state-of-the-art GUI tools such as Motif, Qt, and Java etc. The richness of the collaboration realizes various user interfaces to the Geant4 command system. The following interfaces is currently available;

1. Character terminal (dumb terminal and tcsh-like terminal), that is the default user interface of Geant4
2. Xm, Xaw, Win32, Qt variations of the above terminal by using a Motif, Athena, Qt or Windows widget
3. GAG, a fully graphical user interface and its network extension GainServer of the client/server type.

Implementation of the user sesssions (1 and 2) is included in the `source/interfaces/basic` directory. As for GAG, the front-end class is included in the source/interfaces/GAG directory, while its partner GUI package MOMO.jar is available under the `environments/MOMO` directory. MOMO.jar, Java archive file, contains not only GAG, but also GGE and other helper packages. Supplementary information is available from the author's web page (see URL below).

GAG, GainServer's client GUI Gain: http://www-geant4.kek.jp/~yoshidah

2.8.2. A Short Description of Available Interface Classes

2.8.2.1. *G4UIterminal* and *G4UItcsh* classes

These interfaces open a session on the character terminal. *G4UIterminal* runs on all platforms supported by Geant4, including *cygwin* on Windows. The following built-in commands are available in *G4UIterminal*;

cd, pwd
: change, display the current command directory.

ls, lc
: list commands and subdirectories in the current directory.

history
: show previous commands.

!historyID
: reissue previous command.

?command
: show current parameter values of the command.

help command
: show command help.

exit
: terminate the session.

G4UItcsh supports user-friendly key bindings a-la-tcsh. *G4UItcsh* runs on Solaris and Linux. The following key-bindings are supported;

^A
: move cursor to the top

^B
: backward cursor ([LEFT] cursor)

^C (except Windows terminal)
: abort a run (*soft abort*) during event processing. A program will be terminated while accepting a user command.

^D
: delete/exit/show matched list

^E
: move cursor to the end

^F
: forward cursor ([RIGHT] cursor)

^K
: clear after the cursor

^N
: next command ([DOWN] cursor)

^P
: previous command ([UP] cursor)

TAB
: command completion

DEL
: backspace

BS
: backspace

The example below shows how to set a user's prompt.

```
G4UItcsh* tcsh = new G4UItcsh();
tcsh-> SetPrompt("%s>");
```

The following strings are supported as substitutions in a prompt string.

%s
: current application status

%/
: current working directory

%h
history number

Command history in a user's session is saved in a file `$(HOME)/.g4_hist` that is automatically read at the next session, so that command history is available across sessions.

2.8.2.2. *G4UIXm*, *G4UIXaw*, *G4UIQt* and *G4UIWin32* classes

These interfaces are versions of *G4UIterminal* implemented over libraries Motif, Athena, Qt and WIN32 respectively. *G4UIXm* uses the Motif XmCommand widget, *G4UIXaw* the Athena dialog widget, *G4UIQt* the Qt dialog widget, and *G4UIWin32* the Windows "edit" component to do the command capturing. These interfaces are useful if working in conjunction with visualization drivers that use the Xt library, Qt library or the WIN32 one.

A command box is at disposal for entering or recalling Geant4 commands. Command completion by typing "TAB" key is available in the command box. The shell commands "exit, cont, help, ls, cd..." are also supported. A menu bar can be customized through the *AddMenu* and *AddButton* method. Ex:

/gui/addMenu
test Test

/gui/addButton
test Init /run/initialize

/gui/addButton
test "Set gun" "/control/execute gun.g4m"

/gui/addButton
test "Run one event" "/run/beamOn 1"

G4UIXm runs on Unix/Linux with Motif. *G4UIXaw*, less user friendly, runs on Unix with Athena widgets. *G4UIQt* run everywhere with Qt. *G4UIWin32* runs on Windows.

2.8.2.3. *G4UIGAG* and *G4UIGainServer* classes

They are the front-end classes of Geant4 which make connection with their respective graphical user interfaces, GAG (Geant4 Adaptive GUI) via pipe, and Gain (Geant4 adaptive interface for network) via sockets. While GAG must run on the same system (Windows or Unixen) as a Geant4 application, Gain can run on a remote system (Windows, Linux, etc.) in which JRE (Java Runtime Environment) is installed. A Geant4 application is invoked on a Unix (Linux) system and behaves as a network server. It opens a port, waiting the connection from the Gain. Gain is capable to connect to multiple Geant4 "servers" on Unixen systems at different institutes.

Client GUIs, GAG and Gain have almost similar look-and-feel. So, GAG's functionalities are briefly explained here. Please refer to the URL previously mentioned for details.

Using GAG, user can select a command, set its parameters and execute it. It is adaptive, in the sense that it reflects the internal states of Geant4 that is a state machine. So, GAG always provides users with the Geant4 commands which may be added, deleted, enabled or disabled during a session. GAG does nothing by itself but to play an intermediate between user and an executable simulation program via pipes. Geant4's front-end class *G4UIGAG* must be instantiated to communicate with GAG. GAG runs on Linux and Windows. MOMO.jar can be run by a command;

```
%java -jar  $G4INSTALL/environments/MOMO/MOMO.jar
```

GAG has following functions.

GAG Menu:
The menus are to choose and run a Geant4 executable file, to kill or exit a Geant4 process and to exit GAG. Upon the normal exit or an unexpected death of the Geant4 process, GAG window are automatically reset to run another Geant4 executable.

Geant4 Command tree:

Upon the establishment of the pipe connection with the Geant4 process, GAG displays the command menu, using expandable tree browser whose look and feel is similar to a file browser. Disabled commands are shown in opaque. GAG doesn't display commands that are just below the root of the command hierarchy. Direct type-in field is available for such input. Guidance of command categories and commands are displayed upon focusing. GAG has a command history function. User can re-execute a command with old parameters, edit the history, or save the history to create a macro file.

Command Parameter panel:

GAG's parameter panel is the user-friendliest part. It displays parameter name, its guidance, its type(s) (integer, double, Boolean or string), omittable, default value(s), expression(s) of its range and candidate list(s) (for example, of units). Range check is done by intercoms and the error message from it is shown in the pop-up dialog box. When a parameter component has a candidate list, a list box is automatically displayed . When a file is requested by a command, the file chooser is available.

Logging:

Log can be redirected to the terminal (xterm or cygwin window) from which GAG is invoked. It can be interrupted as will, in the middle of a long session of execution. Log can be saved to a file independent of the above redirection . GAG displays warning or error messages from Geant4 in a pop-up warning widget.

2.8.3. Building the Interface Libraries

The libraries that do not depend on external packages are created by default, using Geant4 configure scripts. They include *G4UIterminal*, *G4UItcsh* and *G4UIGAG* in libraries *libG4UIbasic.a/so* and *libG4UIGAG.a/so*. *G4UIGainServer.o* is packed in the *libG4UIGAG*.

To make the libraries of *G4UIXm*, *G4UIXaw*, *G4UIQt* and *G4UIWin32* , respective environment variables **G4UI_BUILD_XM_SESSION**, **G4UI_BUILD_XAW_SESSION**, **G4UI_BUILD_QT_SESSION** and **G4UI_BUILD_WIN32_SESSION** must be set explicitly before creating libraries.

If the environment variable **G4UI_NONE** is set, no interface libraries are built at all.

The scheme of building the user interface libraries is specified in "$G4INSTALL/config/G4UI_BUILD.gmk" makefile and the dependencies on the external packages are specified in "$G4INSTALL/config/interactivity.gmk".

2.8.4. How to Use the Interface in Your Application

To use a given interface (`G4UIxxx` where `xxx = terminal,Xm, Xaw, Win32, Qt, GAG, GainServer`) in your program, there are two ways.

- Calling G4UIxxx directly :

```
   #include "G4Uixxx.hh"
// to instantiate a session of your choice and start the session
   G4UIsession* session = new G4UIxxx;
   session->SessionStart();
// the line next to the "SessionStart" is necessary to finish the session
   delete session;
```

If you want to select a session type according to your environment variable, the code can be:

```
// to include the class definition in the main program:
   #if defined(G4UI_USE_TCSH)
     #include "G4UIterminal.hh"
     #include "G4UItcsh.hh"
   #elif defined(G4UI_USE_XM)
     #include "G4UIXm.hh"
   ....
   #endif

   #if defined(G4UI_USE_TCSH)
```

```
    session = new G4UITerminal(new G4UItcsh);
  #elif defined(G4UI_USE_XM)
    session = new G4UIXm(argc,argv);
  #elif ...
```

Note : For a tcsh session, the second line must be

```
    G4UIsession* session = new G4UIterminal(new G4UItcsh);
```

If the user wants to deactivate the default signal handler (soft abort) raised by "Ctr-C", the false flag can be set in the second argument of the *G4UIterminal* constructor like;

```
  G4UIsession* session = new G4UIterminal(new G4UItcsh, false).
```

- Using *G4UIExecutive* (implemented in all novice examples) : The above code is rather troublesome. This is more convenient way for choosing a session type.

```
// to include the class definition in the main program:
   #ifdef G4UI_USE
     #include "G4UIExecutive.hh"
   #endif
// to instantiate a session of your choice and start the session
   #ifdef G4UI_USE
     G4UIExecutive* ui = new G4UIExecutive(argc,argv);
     ui->SessionStart();
// the line next to the "SessionStart" is necessary to finish the session
     delete ui;
   #endif
```

A corresponding environment variable must be preset to select a given interface. But some of them are set by defaults for your convenience.

- *G4UIterminal*, *G4UItcsh*, *G4UIGAG* and *G4UIGainServer* can be used without setting any environment variables. Sessions not needing external packages or libraries are always built (see "G4UI_BUILD.gmk") and linked, so the user can instantiate one of these sessions without rebuilding the libraries and without setting any environment variables.
- The environment variable **G4UI_USE_XM**, **G4UI_USE_QT**, **G4UI_USE_XAW** or **G4UI_USE_WIN32** must be set to use the respective interface. The file "$G4INSTALL/config/G4UI_USE.gmk" resolves their dependencies on external packages.
- If the environment variable **G4UI_NONE** is set, no external libraries are selected. Also, for your convenience, if any **G4UI_USE_XXX** environment variable is set, then the corresponding C-pre-processor flag is also set. However, if the environment variable **G4UI_NONE** is set, no C-pre-processor flags are set.

2.9. How to Execute a Program

2.9.1. Introduction

A Geant4 application can be run either in

- `purely hard-coded` batch mode
- batch mode, but reading a macro of commands
- interactive mode, driven by command lines
- interactive mode via a Graphical User Interface

The last mode will be covered in Section 2.8. The first three modes are explained here.

2.9.2. 'Hard-coded' Batch Mode

Below is an example of the main program for an application which will run in batch mode.

Example 2.20. An example of the `main()` routine for an application which will run in batch mode.

```
int main()
{
  // Construct the default run manager
  G4RunManager* runManager = new G4RunManager;

  // set mandatory initialization classes
  runManager->SetUserInitialization(new ExN01DetectorConstruction);
  runManager->SetUserInitialization(new ExN01PhysicsList);

  // set mandatory user action class
  runManager->SetUserAction(new ExN01PrimaryGeneratorAction);

  // Initialize G4 kernel
  runManager->Initialize();

  // start a run
  int numberOfEvent = 1000;
  runManager->BeamOn(numberOfEvent);

  // job termination
  delete runManager;
  return 0;
}
```

Even the number of events in the run is `frozen`. To change this number you must at least recompile `main()`.

2.9.3. Batch Mode with Macro File

Below is an example of the main program for an application which will run in batch mode, but reading a file of commands.

Example 2.21. An example of the `main()` routine for an application which will run in batch mode, but reading a file of commands.

```
int main(int argc,char** argv) {

   // Construct the default run manager
  G4RunManager * runManager = new G4RunManager;

  // set mandatory initialization classes
  runManager->SetUserInitialization(new MyDetectorConstruction);
  runManager->SetUserInitialization(new MyPhysicsList);

  // set mandatory user action class
  runManager->SetUserAction(new MyPrimaryGeneratorAction);

  // Initialize G4 kernel
  runManager->Initialize();

  //read a macro file of commands
  G4UImanager * UI = G4UImanager::getUIpointer();
  G4String command = "/control/execute ";
  G4String fileName = argv[1];
  UI->applyCommand(command+fileName);

  delete runManager;
  return 0;
}
```

This example will be executed with the command:

```
   > myProgram  run1.mac
```

where `myProgram` is the name of your executable and `run1.mac` is a macro of commands located in the current directory, which could look like:

Example 2.22. A typical command macro.

```
#
# Macro file for "myProgram.cc"
#
# set verbose level for this run
#
/run/verbose      2
/event/verbose    0
/tracking/verbose 1
#
# Set the initial kinematic and run 100 events
# electron 1 GeV to the direction (1.,0.,0.)
#
/gun/particle e-
/gun/energy 1 GeV
/run/beamOn 100
```

Indeed, you can re-execute your program with different run conditions without recompiling anything.

Digression: many G4 category of classes have a verbose flag which controls the level of 'verbosity'.

Usually `verbose=0` means silent. For instance

- `/run/verbose` is for the `RunManager`
- `/event/verbose` is for the `EventManager`
- `/tracking/verbose` is for the `TrackingManager`
- ...etc...

2.9.4. Interactive Mode Driven by Command Lines

Below is an example of the main program for an application which will run interactively, waiting for command lines entered from the keyboard.

Example 2.23. An example of the `main()` routine for an application which will run interactively, waiting for commands from the keyboard.

```
int main(int argc,char** argv) {

  // Construct the default run manager
  G4RunManager * runManager = new G4RunManager;

  // set mandatory initialization classes
  runManager->SetUserInitialization(new MyDetectorConstruction);
  runManager->SetUserInitialization(new MyPhysicsList);

  // visualization manager
  G4VisManager* visManager = new G4VisExecutive;
  visManager->Initialize();

  // set user action classes
  runManager->SetUserAction(new MyPrimaryGeneratorAction);
  runManager->SetUserAction(new MyRunAction);
  runManager->SetUserAction(new MyEventAction);
  runManager->SetUserAction(new MySteppingAction);

  // Initialize G4 kernel
  runManager->Initialize();

  // Define UI terminal for interactive mode
  G4UIsession * session = new G4UIterminal;
  session->SessionStart();
  delete session;

  // job termination
  delete visManager;
  delete runManager;

  return 0;
}
```

This example will be executed with the command:

```
> myProgram
```

where `myProgram` is the name of your executable.

The G4 kernel will prompt:

```
Idle>
```

and you can start your session. An example session could be:

Create an empty scene ("world" is default):

```
Idle> /vis/scene/create
```

Add a volume to the scene:

```
Idle> /vis/scene/add/volume
```

Create a scene handler for a specific graphics system. Change the next line to choose another graphic system:

```
Idle> /vis/sceneHandler/create OGLIX
```

Create a viewer:

```
Idle> /vis/viewer/create
```

Draw the scene, etc.:

```
Idle> /vis/scene/notifyHandlers
Idle> /run/verbose      0
Idle> /event/verbose    0
Idle> /tracking/verbose 1
Idle> /gun/particle mu+
Idle> /gun/energy 10 GeV
Idle> /run/beamOn 1
Idle> /gun/particle proton
Idle> /gun/energy 100 MeV
Idle> /run/beamOn 3
Idle> exit
```

For the meaning of the machine state `Idle`, see Section 3.4.2.

This mode is useful for running a few events in debug mode and visualizing them. Notice that the *VisManager* is created in the `main()`, and the visualization system is choosen via the command:

```
/vis/sceneHandler/create OGLIX
```

2.9.5. General Case

Most of the examples in the `$G4INSTALL/examples/` directory have the following `main()`. The application can be run either in batch or interactive mode.

Example 2.24. The typical `main()` routine from the examples directory.

```
int main(int argc,char** argv) {

  // Construct the default run manager
  G4RunManager * runManager = new G4RunManager;

  // set mandatory initialization classes
  N03DetectorConstruction* detector = new N03DetectorConstruction;
  runManager->SetUserInitialization(detector);
  runManager->SetUserInitialization(new N03PhysicsList);

#ifdef G4VIS_USE
  // visualization manager
  G4VisManager* visManager = new G4VisExecutive;
  visManager->Initialize();
#endif

  // set user action classes
  runManager->SetUserAction(new N03PrimaryGeneratorAction(detector));
  runManager->SetUserAction(new N03RunAction);
  runManager->SetUserAction(new N03EventAction);
  runManager->SetUserAction(new N03SteppingAction);

  // get the pointer to the User Interface manager
    G4UImanager* UI = G4UImanager::GetUIpointer();

  if (argc==1)   // Define UI terminal for interactive mode
    {
     G4UIExecutive* session = new G4UIExecutive(argc, argv);
     UI->ApplyCommand("/control/execute prerunN03.mac");
     session->SessionStart();
     delete session;
    }
  else           // Batch mode
    {
     G4String command = "/control/execute ";
     G4String fileName = argv[1];
     UI->ApplyCommand(command+fileName);
    }

  // job termination
#ifdef G4VIS_USE
  delete visManager;
#endif
  delete runManager;

  return 0;
}
```

Notice that the visualization system is under the control of the precompiler variable `G4VIS_USE`. Notice also that, in interactive mode, few intializations have been put in the macro `prerunN03.mac` which is executed before the session start.

Example 2.25. The `prerunN03.mac` macro.

```
# Macro file for the initialization phase of "exampleN03.cc"
#
# Sets some default verbose flags
# and initializes the graphics.
#
/control/verbose 2
/control/saveHistory
/run/verbose 2
#
/run/particle/dumpCutValues
#
# Create empty scene ("world" is default)
/vis/scene/create
#
# Add volume to scene
/vis/scene/add/volume
#
# Create a scene handler for a specific graphics system
# Edit the next line(s) to choose another graphic system
#
#/vis/sceneHandler/create DAWNFILE
/vis/sceneHandler/create OGLIX
#
# Create a viewer
/vis/viewer/create
#
# Draw scene
/vis/scene/notifyHandlers
#
# for drawing the tracks
# if too many tracks cause core dump => storeTrajectory 0
/tracking/storeTrajectory 1
#/vis/scene/include/trajectories
```

Also, this example demonstrates that you can read and execute a macro interactively:

```
 Idle> /control/execute  mySubMacro.mac
```

2.10. How to Visualize the Detector and Events

2.10.1. Introduction

This section briefly explains how to perform Geant4 Visualization. The description here is based on the sample program `examples/novice/N03`. More details are given in Chapter 8 "Visualization". Example macro files can be found in `examples/novice/N03/visTutor/exN03VisX.mac`.

2.10.2. Visualization Drivers

The Geant4 visualization system was developed in response to a diverse set of requirements:

1. Quick response to study geometries, trajectories and hits
2. High-quality output for publications
3. Flexible camera control to debug complex geometries
4. Tools to show volume overlap errors in detector geometries
5. Interactive picking to get more information on visualized objects

No one graphics system is ideal for all of these requirements, and many of the large software frameworks into which Geant4 has been incorporated already have their own visualization systems, so Geant4 visualization was designed around an abstract interface that supports a diverse family of graphics systems. Some of these graphics systems use a graphics library compiled with Geant4, such as OpenGL, Qt or OpenInventor, while others involve a separate application, such as HepRApp or DAWN.

You need not use all visualization drivers. You can select those suitable to your purposes. In the following, for simplicity, we assume that the Geant4 libraries are built (installed) with the "OpenGL-Xlib driver" and the "DAWNFILE driver" incorporated.

In order to use the DAWNFILE driver, you need Fukui Renderer DAWN, which is obtainable from the following Web site: http://geant4.kek.jp/GEANT4/vis.

In order to use the the OpenGL drivers, you need the OpenGL library, which is installed in many platforms by default. You also need to set an environmental variable `G4VIS_BUILD_OPENGLX_DRIVER` to `1` in building (installing) Genat4 libraries, and also set another environmental variable `G4VIS_USE_OPENGLX` to `1` in compiling your Geant4 executable. You may also have to set an environmental variable `OGLHOME` to the OpenGL root directory. For example,

```
setenv G4VIS_BUILD_OPENGLX_DRIVER 1
setenv G4VIS_USE_OPENGLX 1
setenv OGLHOME /usr/X11R6
```

Some other visualization drivers depending on external libraries are also required to set the similar environmental variables, `G4VIS_BUILD_DRIVERNAME_DRIVER` and `G4VIS_USE_DRIVERNAME`, to `1`. All visualization drivers independent of external libraries, e.g. DAWNFILE and VRMLFILE drivers, need not such setting. (But you must prepare a proper visualization manager class and a proper `main()` function, anyway. See below.)

For all visualization drivers available in your Geant4 executable, the C-pre-processor flags `G4VIS_USE_DRIVERNAME` are automatically set by `config/G4VIS_USE.gmk` in compilation. Similarly, for all visualization drivers incorporated into the Geant4 libraries, the C-pre-processor flags `G4VIS_BUILD_DRIVERNAME_DRIVER` are automatically set by `config/G4VIS_BUILD.gmk` in installation.

2.10.3. How to Incorporate Visualization Drivers into an Executable

You can realize (use) visualization driver(s) you want in your Geant4 executable. These can only be from the set installed in the Geant4 libraries. You will be warned if the one you request is not available.

In order to realize visualization drivers, you must instantiate and initialize a subclass of `G4VisManager` that implements the pure virtual function `RegisterGraphicsSystems()`. This subclass must be compiled in the user's domain to force the loading of appropriate libraries in the right order. The easiest way to do this is to use `G4VisExecutive`, a provided class with included implementation. `G4VisExecutive` is sensitive to the `G4VIS_USE...` variables mentioned above.

If you do wish to write your own subclass, you may do so. You will see how to do this by looking at `G4VisExecutive.icc`. A typical extract is:

```
...
  RegisterGraphicsSystem (new G4DAWNFILE);
...
#ifdef G4VIS_USE_OPENGLX
  RegisterGraphicsSystem (new G4OpenGLImmediateX);
  RegisterGraphicsSystem (new G4OpenGLStoredX);
#endif
...
```

If you wish to use `G4VisExecutive` but register an additional graphics system, `XXX` say, you may do so either before or after initializing:

```
visManager->RegisterGraphicsSytem(new XXX);
visManager->Initialize();
```

An example of a typical `main()` function is given below.

2.10.4. Writing the `main()` Method to Include Visualization

Now we explain how to write a visualization manager and the `main()` function for Geant4 visualization. In order that your Geant4 executable is able to perform visualization, you must instantiate and initialize *your* Visualiza-

tion Manager in the `main()` function. The typical `main()` function available for visualization is written in the following style:

Example 2.26. The typical `main()` routine available for visualization.

```
//----- C++ source codes: main() function for visualization
#ifdef G4VIS_USE
#include "G4VisExecutive.hh"
#endif

.....

int main(int argc,char** argv) {

.....

  // Instantiation and initialization of the Visualization Manager
#ifdef G4VIS_USE
  // visualization manager
  G4VisManager* visManager = new G4VisExecutive;
  visManager->Initialize();
#endif

.....

  // Job termination
#ifdef G4VIS_USE
  delete visManager;
#endif

.....

  return 0;
}

//----- end of C++
```

In the instantiation, initialization, and deletion of the Visualization Manager, the use of the macro `G4VIS_USE` is recommended. This is set unless the environment variable `G4VIS_NONE` is set. This allows one easily to build an executable without visualization, if required, without changing the code (but remember you have to force re-compilation whenever you change the environment). Note that it is your responsibility to delete the instantiated Visualization Manager by yourself. A complete description of a sample `main()` function is described in `examples/novice/N03/exampleN03.cc`.

2.10.5. Sample Visualization Sessions

In this section we present typical sessions of Geant4 visualization. You can test them with the sample program geant4/examples/novice/N03. Run a binary executable "exampleN03" without an argument, and then execute the commands below in the "Idle>" state. Explanation of each command will be described later. (Note that the OpenGL-Xlib driver, Qt driver and the DAWNFILE driver are incorporated into the executable, and that Fukui Renderer DAWN is installed in your machine.)

2.10.5.1. Visualization of detector components

The following session visualizes detector components with the OpenGL-Xlib driver and then with the DAWNFILE driver. The former exhibits minimal visualization commands to visualize detector geometry, while the latter exhibits customized visualization (visualization of a selected physical volume, coordinate axes, texts, etc).

```
#################################################
#  vis1.mac:
#    A Sample macro to demonstrate visualization
#    of detector geometry.
#
#  USAGE:
#   Save the commands below as a macro file, say,
#   "vis1.mac", and execute it as follows:
#
```

```
#   % $(G4BINDIR)/exampleN03
#   Idle> /control/execute vis1.mac
##############################################

##############################################
# Visualization of detector geometry
#  with the OGLIX (OpenGL Immediate X) driver
##############################################

# Invoke the OGLIX driver:
#  Create a scene handler and a viewer for the OGLIX driver
/vis/open OGLIX

# Visualize the whole detector geometry
#  with the default camera parameters.
#  Command "/vis/drawVolume" visualizes the detector geometry,
#  and command "/vis/viewer/flush" declares the end of visualization.
#  (The command /vis/viewer/flush  can be omitted for the OGLIX
#   and OGLSX drivers.)
#  The default argument of "/vis/drawVolume" is "world".
/vis/drawVolume
/vis/viewer/flush

########################################
# Visualization with the DAWNFILE driver
########################################

# Invoke the DAWNFILE driver
#  Create a scene handler and a viewer for the DAWNFILE driver
/vis/open DAWNFILE

# Bird's-eye view of a detector component (Absorber)
#  drawing style: hidden-surface removal
#  viewpoint  : (theta,phi) = (35*deg, 45*deg),
#  zoom factor: 1.1 of the full screen size
#  coordinate axes:
#     x-axis:red,  y-axis:green,  z-axis:blue
#     origin: (0,0,0),  length: 500 mm
#
/vis/viewer/reset
/vis/viewer/set/style          surface
/vis/viewer/zoom               1.1
/vis/viewer/set/viewpointThetaPhi  35 45
/vis/drawVolume                Absorber
/vis/scene/add/axes            0 0 0 500 mm
/vis/scene/add/text            0 0 0 mm  40 -100 -140   Absorber
/vis/viewer/flush

# Bird's-eye view of the whole detector components
#  * "/vis/viewer/set/culling global false" makes the invisible
#    world volume visible.
#    (The invisibility of the world volume is set
#     in ExN03DetectorConstruction.cc.)
/vis/viewer/set/style     wireframe
/vis/viewer/set/culling   global false
/vis/drawVolume
/vis/scene/add/axes       0 0 0 500 mm
/vis/scene/add/text       0 0 0 mm 50 -50 -200   world
/vis/viewer/flush
################### END of vis1.mac ###################
```

2.10.5.2. Visualization of events

The following session visualizes events (tajectories) with the OpenGL-Xlib driver and then with the DAWNFILE driver. The former exhibits minimal visualization commands to visualize events, while the latter exhibits customized visualization. Note that the run action and event action classes should be described properly. (See, for example, the following classes: "examples/novice/N03/src/ExN03RunAction.cc",

```
#####################################################
#  vis2.mac:
#    A Sample macro to demonstrate visualization
#    of events (trajectories).
#
#  USAGE:
```

```
#   Save the commands below as a macro file, say,
#   "vis2.mac", and execute it as follows:
#
#   % $(G4BINDIR)/exampleN03
#   Idle> /control/execute vis1.mac
###############################################

#########################################################
# Store particle trajectories for visualization
/tracking/storeTrajectory 1
#########################################################

#########################################################
# Visualization with the OGLSX (OpenGL Stored X) driver
#########################################################

# Invoke the OGLSX driver
#  Create a scene handler and a viewer for the OGLSX driver
/vis/open OGLSX

# Create an empty scene and add detector components to it
/vis/drawVolume

# Add trajectories to the current scene
#  Note: This command is not necessary in, e.g.,
#        examples/novice/N03, since the C++ method DrawTrajectory()
#        is described in the event action.
#/vis/scene/add/trajectories

# Set viewing parameters
/vis/viewer/reset
/vis/viewer/set/viewpointThetaPhi  10 20

# Visualize one it.
/run/beamOn 1

#############################################################
# Visualization with the DAWNFILE driver
#############################################################

# Invoke the DAWNFILE driver
#  Create a scene handler and a viewer for the DAWNFILE driver
/vis/open DAWNFILE

# Create an empty scene and add detector components to it
/vis/drawVolume

# Add trajectories to the current scene
#  Note: This command is not necessary in exampleN03,
#        since the C++ method DrawTrajectory() is
#        described in the event action.
#/vis/scene/add/trajectories

# Visualize plural events (bird's eye view)
#  drawing style: wireframe
#  viewpoint  : (theta,phi) = (45*deg, 45*deg)
#  zoom factor: 1.5 x (full screen size)
/vis/viewer/reset
/vis/viewer/set/style  wireframe
/vis/viewer/set/viewpointThetaPhi   45 45
/vis/viewer/zoom        1.5
/run/beamOn             2

# Set the drawing style to "surface"
#  Candidates: wireframe, surface
/vis/viewer/set/style  surface

# Visualize plural events (bird's eye view) again
#  with another drawing style (surface)
/run/beamOn             2

################### END of vis2.mac ###################
```

2.10.6. For More Information on Geant4 Visualization

See the Chapter 8 "Visualization" part of this user guide.

Chapter 3. Toolkit Fundamentals

3.1. Class Categories and Domains

3.1.1. What is a class category?

In the design of a large software system such as Geant4, it is essential to partition it into smaller logical units. This makes the design well organized and easier to develop. Once the logical units are defined independent to each other as much as possible, they can be developed in parallel without serious interference.

In object-oriented analysis and design methodology by Grady Booch [Booch1994] , class categories are used to create logical units. They are defined as "clusters of classes that are themselves cohesive, but are loosely coupled relative to other clusters." This means that a class category contains classes which have a close relationship (for example, the "has-a" relation). However, relationships between classes which belong to different class categories are weak, i.e., only limitted classes of these have "uses" relations. The class categories and their relations are presented by a class category diagram. The class category diagram designed for Geant4 is shown in the figure below. Each box in the figure represents a class category, and a "uses" relation by a straight line. The circle at an end of a straight line means the class category which has this circle uses the other category.

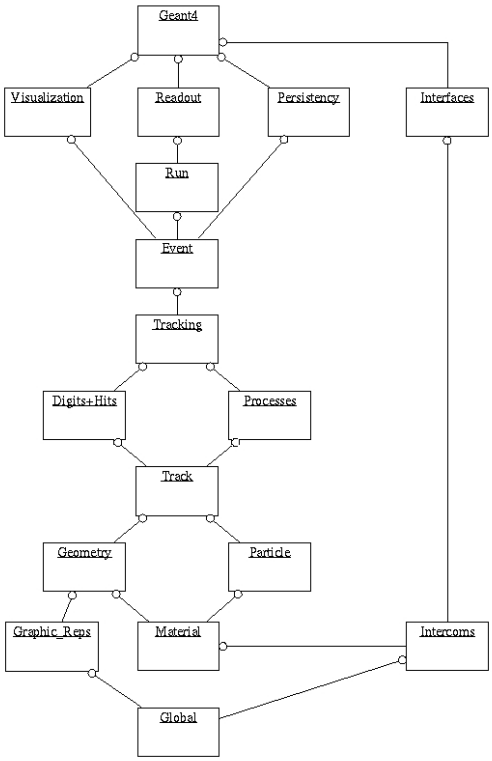


Figure 3.1. Geant4 class categories

The file organization of the Geant4 codes follows basically the structure of this class cateogory. This *User's Manual* is also organized according to class categories.

In the development and maintenance of Geant4, one software team will be assigned to a class category. This team will have a responsibility to develop and maintain all classes belonging to the class category.

3.1.2. Class categories in Geant4

The following is a brief summary of the role of each class category in Geant4.

1. **Run and Event**

   These are categories related to the generation of events, interfaces to event generators, and any secondary particles produced. Their roles are principally to provide particles to be tracked to the Tracking Management.
2. **Tracking and Track**

   These are categories related to propagating a particle by analyzing the factors limiting the step and applying the relevant physics processes. The important aspect of the design was that a generalized Geant4 physics process (or interaction) could perform actions, along a tracking step, either localized in space, or in time, or distributed in space and time (and all the possible combinations that could be built from these cases).
3. **Geometry and Magnetic Field**

   These categories manage the geometrical definition of a detector (solid modeling) and the computation of distances to solids (also in a magnetic field). The Geant4 geometry solid modeler is based on the ISO STEP standard and it is fully compliant with it, in order to allow in future the exchange of geometrical information with CAD systems. A key feature of the Geant4 geometry is that the volume definitions are independent of the solid representation. By this abstract interface for the G4 solids, the tracking component works identically for various representations. The treatment of the propagation in the presence of fields has been provided within specified accuracy. An OO design allows us to exchange different numerical algorithms and/or different fields (not only B-field), without affecting any other component of the toolkit.
4. **Particle Definition and Matter**

   These two categories manage the the definition of materials and particles.
5. **Physics**

   This category manages all physics processes participating in the interactions of particles in matter. The abstract interface of physics processes allows multiple implementations of physics models per interaction or per channel. Models can be selected by energy range, particle type, material, etc. Data encapsulation and polymorphism make it possible to give transparent access to the cross sections (independently of the choice of reading from an ascii file, or of interpolating from a tabulated set, or of computing analytically from a formula). Electromagnetic and hadronic physics were handled in a uniform way in such a design, opening up the physics to the users.
6. **Hits and Digitization**

   These two categories manage the creation of hits and their use for the digitization phase. The basic design and implementation of the Hits and Digi had been realized, and also several prototypes, test cases and scenarios had been developed before the alpha-release. Volumes (not necessarily the ones used by the tracking) are aggregated in sensitive detectors, while hits collections represent the logical read out of the detector. Different ways of creating and managing hits collections had been delivered and tested, notably for both single hits and calorimetry hits types. In all cases, hits collections had been successfully stored into and retrieved from an Object Data Base Management System.
7. **Visualization**

   This manages the visualization of solids, trajectories and hits, and interacts with underlying graphical libraries (the Visualization class category). The basic and most frequently used graphics functionality had been implemented already by the alpha-release. The OO design of the visualization component allowed us to develop several drivers independently, such as for OpenGL, Qt and OpenInventor (for X11 and Windows), DAWN, Postscript (via DAWN) and VRML.
8. **Interfaces**

   This category handles the production of the graphical user interface (GUI) and the interactions with external software (OODBMS, reconstruction etc.).

3.2. Global Usage Classes

The "global" category in Geant4 collects all classes, types, structures and constants which are considered of general use within the Geant4 toolkit. This category also defines the interface with third-party software libraries (CLHEP, STL, etc.) and system-related types, by defining, where appropriate, `typedef`s according to the Geant4 code conventions.

3.2.1. Signature of Geant4 classes

In order to keep an homogeneous naming style, and according to the Geant4 coding style conventions, each class part of the Geant4 kernel has its name beginning with the prefix *G4*, e.g., *G4VHit, G4GeometryManager, G4ProcessVector*, etc. Instead of the raw C types, *G4* types are used within the Geant4 code. For the basic numeric types (`int, float, double`, etc.), different compilers and different platforms provide different value ranges. In order to assure portability, the use of *G4int, G4float, G4double, G4bool*, globally defined, is preferable. *G4* types implement the right generic type for a given architecture.

3.2.1.1. Basic types

The basic types in Geant4 are considered to be the following:

- *G4int*,
- *G4long*,
- *G4float*,
- *G4double*,
- *G4bool*,
- *G4complex*,
- *G4String*.

which currently consist of simple `typedef`s to respective types defined in the **CLHEP**, **STL** or system libraries. Most definitions of these basic types come with the inclusion of a single header file, `globals.hh`. This file also provides inclusion of required system headers, as well as some global utility functions needed and used within the Geant4 kernel.

3.2.1.2. Typedefs to CLHEP classes and their usage

The following classes are `typedef`s to the corresponding classes of the **CLHEP** (**Computing Library for High Energy Physics**) distribution. For more detailed documentation please refer to the **CLHEP reference guide** and the **CLHEP user manual** .

- *G4ThreeVector, G4RotationMatrix, G4LorentzVector* and *G4LorentzRotation*

  Vector classes: defining 3-component (x,y,z) vector entities, rotation of such objects as 3x3 matrices, 4-component (x,y,z,t) vector entities and their rotation as 4x4 matrices.
- *G4Plane3D, G4Transform3D, G4Normal3D, G4Point3D*, and *G4Vector3D*

  Geometrical classes: defining geometrical entities and transformations in 3D space.

3.2.2. The *HEPRandom* module in CLHEP

The *HEPRandom* module, originally part of the Geant4 kernel, and now distributed as a module of **CLHEP**, has been designed and developed starting from the *Random* class of MC++, the original **CLHEP**'s *HepRandom* module and the **Rogue Wave** approach in the **Math.h++** package. For detailed documentation on the *HEPRandom* classes see the **CLHEP reference guide** and the **CLHEP user manual** .

Information written in this manual is extracted from the original manifesto distributed with the *HEPRandom* package.

The *HEPRandom* module consists of classes implementing different random ``engines'' and different random ``distributions''. A distribution associated to an engine constitutes a random ``generator''. A distribution class can collect different algorithms and different calling sequences for each method to define distribution parameters or range-intervals. An engine implements the basic algorithm for pseudo-random numbers generation.

There are 3 different ways of shooting random values:

1. Using the static generator defined in the *HepRandom* class: random values are shot using static methods `shoot()` defined for each distribution class. The static generator will use, as default engine, a *HepJamesRandom* object, and the user can set its properties or change it with a new instantiated engine object by using the static methods defined in the *HepRandom* class.
2. Skipping the static generator and specifying an engine object: random values are shot using static methods `shoot(*HepRandomEngine)` defined for each distribution class. The user must instantiate an engine object and give it as argument to the shoot method. The generator mechanism will then be by-passed by using the basic `flat()` method of the specified engine. The user must take care of the engine objects he/she instantiates.
3. Skipping the static generator and instantiating a distribution object: random values are shot using `fire()` methods (NOT static) defined for each distribution class. The user must instantiate a distribution object giving as argument to the constructor an engine by pointer or by reference. By doing so, the engine will be associated to the distribution object and the generator mechanism will be by-passed by using the basic `flat()` method of that engine.

In this guide, we'll only focus on the static generator (point 1.), since the static interface of *HEPRandom* is the only one used within the Geant4 toolkit.

3.2.2.1. *HEPRandom* engines

The class *HepRandomEngine* is the abstract class defining the interface for each random engine. It implements the `getSeed()` and `getSeeds()` methods which return the `initial seed' value and the initial array of seeds (if any) respectively. Many concrete random engines can be defined and added to the structure, simply making them inheriting from *HepRandomEngine*. Several different engines are currently implemented in *HepRandom*, we describe here five of them:

- *HepJamesRandom*

  It implements the algorithm described in ``F.James, Comp. Phys. Comm. 60 (1990) 329" for pseudo-random number generation. This is the default random engine for the static generator; it will be invoked by each distribution class unless the user sets a different one.
- *DRand48Engine*

  Random engine using the `drand48()` and `srand48()` system functions from C standard library to implement the `flat()` basic distribution and for setting seeds respectively. *DRand48Engine* uses the `seed48()` function from C standard library to retrieve the current internal status of the generator, which is represented by 3 short values. *DRand48Engine* is the only engine defined in *HEPRandom* which intrinsically works in 32 bits precision. Copies of an object of this kind are not allowed.
- *RandEngine*

  Simple random engine using the `rand()` and `srand()` system functions from the C standard library to implement the `flat()` basic distribution and for setting seeds respectively. Please note that it's well known that the spectral properties of `rand()` leave a great deal to be desired, therefore the usage of this engine is not recommended if a good randomness quality or a long period is required in your code. Copies of an object of this kind are not allowed.
- *RanluxEngine*

  The algorithm for *RanluxEngine* has been taken from the original implementation in FORTRAN77 by Fred James, part of the **MATHLIB HEP** library. The initialisation is carried out using a Multiplicative Congruential generator using formula constants of L'Ecuyer as described in ``F.James, Comp. Phys. Comm. 60 (1990) 329-344". The engine provides five different luxury levels for quality of random generation. When instantiating a *RanluxEngine*, the user can specify the luxury level to the constructor (if not, the default value 3 is taken). For example:

```
RanluxEngine theRanluxEngine(seed,4);
// instantiates an engine with `seed' and the best luxury-level
... or
RanluxEngine theRanluxEngine;
// instantiates an engine with default seed value and luxury-level
...
```

The class provides a `getLuxury()` method to get the engine luxury level.

The `SetSeed()` and `SetSeeds()` methods to set the initial seeds for the engine, can be invoked specifying the luxury level. For example:

```
// static interface
HepRandom::setTheSeed(seed,4);  // sets the seed to `seed' and luxury to 4
HepRandom::setTheSeed(seed);    // sets the seed to `seed' keeping
                                // the current luxury level
```

- *RanecuEngine*

  The algorithm for *RanecuEngine* is taken from the one originally written in FORTRAN77 as part of the **MATHLIB HEP** library. The initialisation is carried out using a Multiplicative Congruential generator using formula constants of L'Ecuyer as described in ``F.James, Comp. Phys. Comm. 60 (1990) 329-344". Handling of seeds for this engine is slightly different than the other engines in *HEPRandom*. Seeds are taken from a seed table given an index, the `getSeed()` method returns the current index of seed table. The `setSeeds()` method will set seeds in the local `SeedTable` at a given position index (if the index number specified exceeds the table's size, `[index%size]` is taken). For example:

```
// static interface
const G4long* table_entry;
table_entry = HepRandom::getTheSeeds();
// it returns a pointer `table_entry' to the local SeedTable
// at the current `index' position. The couple of seeds
// accessed represents the current `status' of the engine itself !
...
G4int index=n;
G4long seeds[2];
HepRandom::setTheSeeds(seeds,index);
// sets the new `index' for seeds and modify the values inside
// the local SeedTable at the `index' position. If the index
// is not specified, the current index in the table is considered.
...
```

  The `setSeed()` method resets the current `status' of the engine to the original seeds stored in the static table of seeds in *HepRandom*, at the specified index.

Except for the *RanecuEngine*, for which the internal status is represented by just a couple of longs, all the other engines have a much more complex representation of their internal status, which currently can be obtained only through the methods `saveStatus()`, `restoreStatus()` and `showStatus()`, which can also be statically called from *HepRandom*. The status of the generator is needed for example to be able to reproduce a run or an event in a run at a given stage of the simulation.

RanecuEngine is probably the most suitable engine for this kind of operation, since its internal status can be fetched/reset by simply using `getSeeds()`/`setSeeds()` (`getTheSeeds()`/`setTheSeeds()` for the static interface in *HepRandom*).

3.2.2.2. The static interface in the *HepRandom* class

HepRandom a singleton class and using a *HepJamesRandom* engine as default algorithm for pseudo-random number generation. *HepRandom* defines a static private data member, `theGenerator`, and a set of static methods to manipulate it. By means of `theGenerator`, the user can change the underlying engine algorithm, get and set the seeds, and use any kind of defined random distribution. The static methods `setTheSeed()` and `getTheSeed()` will set and get respectively the `initial' seed to the main engine used by the static generator. For example:

```
HepRandom::setTheSeed(seed);  // to change the current seed to 'seed'
int startSeed = HepRandom::getTheSeed();  // to get the current initial seed
HepRandom::saveEngineStatus();    // to save the current engine status on file
```

```
HepRandom::restoreEngineStatus(); // to restore the current engine to a previous
                                  // saved configuration
HepRandom::showEngineStatus();    // to display the current engine status to stdout
...
int index=n;
long seeds[2];
HepRandom::getTheTableSeeds(seeds,index);
  // fills `seeds' with the values stored in the global
  // seedTable at position `index'
```

Only one random engine can be active at a time, the user can decide at any time to change it, define a new one (if not done already) and set it. For example:

```
RanecuEngine theNewEngine;
HepRandom::setTheEngine(&theNewEngine);
 ...
```

or simply setting it to an old instantiated engine (the old engine status is kept and the new random sequence will start exactly from the last one previously interrupted). For example:

```
HepRandom::setTheEngine(&myOldEngine);
```

Other static methods defined in this class are:

- `void setTheSeeds(const G4long* seeds, G4int)`
- `const G4long* getTheSeeds()`

  To set/get an array of seeds for the generator, in the case of a *RanecuEngine* this corresponds also to set/get the current status of the engine.
- `HepRandomEngine* getTheEngine()`

  To get a pointer to the current engine used by the static generator.

3.2.2.3. *HEPRandom* distributions

A distribution-class can collect different algorithms and different calling sequences for each method to define distribution parameters or range-intervals; it also collects methods to fill arrays, of specified size, of random values, according to the distribution. This class collects either static and not static methods. A set of distribution classes are defined in *HEPRandom*. Here is the description of some of them:

- *RandFlat*

  Class to shoot flat random values (integers or double) within a specified interval. The class provides also methods to shoot just random bits.
- *RandExponential*

  Class to shoot exponential distributed random values, given a mean (default mean = 1)
- *RandGauss*

  Class to shoot Gaussian distributed random values, given a mean (default = 0) or specifying also a deviation (default = 1). Gaussian random numbers are generated two at the time, so every other time a number is shot, the number returned is the one generated the time before.
- *RandBreitWigner*

  Class to shoot numbers according to the Breit-Wigner distribution algorithms (plain or mean^2).
- *RandPoisson*

  Class to shoot numbers according to the Poisson distribution, given a mean (default = 1) (Algorithm taken from ``W.H.Press et al., Numerical Recipes in C, Second Edition").

3.2.3. The *HEPNumerics* module

A set of classes implementing numerical algorithms has been developed in Geant4. Most of the algorithms and methods have been implemented mainly based on recommendations given in the books:

- B.H. Flowers, ``An introduction to Numerical Methods In C++", Claredon Press, Oxford 1995.
- M. Abramowitz, I. Stegun, ``Handbook of mathematical functions", DOVER Publications INC, New York 1965 ; chapters 9, 10, and 22.

This set of classes includes:

- *G4ChebyshevApproximation*

  Class creating the Chebyshev approximation for a function pointed by fFunction data member. The Chebyshev polynomial approximation provides an efficient evaluation of the minimax polynomial, which (among all polynomials of the same degree) has the smallest maximum deviation from the true function.
- *G4DataInterpolation*

  Class providing methods for data interpolations and extrapolations: Polynomial, Cubic Spline, ...
- *G4GaussChebyshevQ*
- *G4GaussHermiteQ*
- *G4GaussJacobiQ*
- *G4GaussLaguerreQ*

  Classes implementing the Gauss-Chebyshev, Gauss-Hermite, Gauss-Jacobi, Gauss-Laguerre and Gauss-Legendre quadrature methods. Roots of orthogonal polynomials and corresponding weights are calculated based on iteration method (by bisection Newton algorithm).
- *G4Integrator*

  Template class collecting integrator methods for generic functions (Legendre, Simpson, Adaptive Gauss, Laguerre, Hermite, Jacobi).
- *G4SimpleIntegration*

  Class implementing simple numerical methods (Trapezoidal, MidPoint, Gauss, Simpson, Adaptive Gauss, for integration of functions with signature: double f(double).

3.2.4. General management classes

The `global' category defines also a set of `utility' classes generally used within the kernel of Geant4. These classes include:

- *G4Allocator*

  A class for fast allocation of objects to the heap through paging mechanism. It's meant to be used by associating it to the object to be allocated and defining for it `new` and `delete` operators via `MallocSingle()` and `FreeSingle()` methods of *G4Allocator*.

  Note: `G4Allocator` assumes that objects being allocated have all the same size for the type they represent. For this reason, classes which are handled by `G4Allocator` should *avoid* to be used as base-classes for others. Similarly, base-classes of sub-classes handled through `G4Allocator` should not define their (eventually empty) virtual destructors inlined; such measure is necessary in order also to prevent bad aliasing optimisations by compilers which may potentially lead to crashes in the attempt to free allocated chunks of memory when using the base-class pointer or not.

  The list of allocators implicitely defined and used in Geant4 is reported here:

```
    - events (G4Event): anEventAllocator
```

```
      - tracks (G4Track): aTrackAllocator
      - stacked tracks (G4StackedTrack): aStackedTrackAllocator
      - primary particles (G4PrimaryParticle): aPrimaryParticleAllocator
      - primary vertices (G4PrimaryVertex): aPrimaryVertexAllocator
      - decay products (G4DecayProducts): aDecayProductsAllocator
      - digits collections of an event (G4DCofThisEvent): anDCoTHAllocator
      - digits collections (G4DigiCollection): aDCAllocator
      - hits collections of an event (G4HCofThisEvent): anHCoTHAllocator
      - hits collections (G4HitsCollection): anHCAllocator
      - touchable histories (G4TouchableHistory): aTouchableHistoryAllocator
      - trajectories (G4Trajectory): aTrajectoryAllocator
      - trajectory points (G4TrajectoryPoint): aTrajectoryPointAllocator
      - trajectory containers (G4TrajectoryContainer): aTrajectoryContainerAllocator
      - navigation levels (G4NavigationLevel): aNavigationLevelAllocator
      - navigation level nodes (G4NavigationLevelRep): aNavigLevelRepAllocator
      - reference-counted handles (G4ReferenceCountedHandle<X>): aRCHAllocator
      - counted objects (G4CountedObject<X>): aCountedObjectAllocator
      - HEPEvt primary particles (G4HEPEvtParticle): aHEPEvtParticleAllocator
      - electron occupancy objects(G4ElectronOccupancy): aElectronOccupancyAllocator
      - "rich" trajectories (G4RichTrajectory): aRichTrajectoryAllocator
      - "rich" trajectory points (G4RichTrajectoryPoint): aRichTrajectoryPointAllocator
      - "smooth" trajectories (G4SmoothTrajectory): aSmoothTrajectoryAllocator
      - "smooth" trajectory points (G4SmoothTrajectoryPoint): aSmoothTrajectoryPointAllocator
      - "ray" trajectories (G4RayTrajectory): G4RayTrajectoryAllocator
      - "ray" trajectory points (G4RayTrajectoryPoint): G4RayTrajectoryPointAllocator
```

For each of these allocators, accessible from the global namespace, it is possible to monitor the allocation in their memory pools or force them to release the allocated memory (for example at the end of a run):

```
      // Return the size of the total memory allocated for tracks
      //
      aTrackAllocator.GetAllocatedSize();

      // Return allocated storage for tracks to the free store
      //
      aTrackAllocator.ResetStorage();
```

- *G4ReferenceCountedHandle*

  Template class acting as a smart pointer and wrapping the type to be counted. It performs the reference counting during the life-time of the counted object.
- *G4FastVector*

  Template class defining a vector of pointers, not performing boundary checking.
- *G4PhysicsVector*

  Defines a physics vector which has values of energy-loss, cross-section, and other physics values of a particle in matter in a given range of the energy, momentum, etc. This class serves as the base class for a vector having various energy scale, for example like 'log' (*G4PhysicsLogVector*) 'linear' (*G4PhysicsLinearVector*), 'free' (*G4PhysicsFreeVector*), etc.
- *G4LPhysicsFreeVector*

  Implements a free vector for low energy physics cross-section data. A subdivision method is used to find the energy|momentum bin.
- *G4PhysicsOrderedFreeVector*

  A physics ordered free vector inherits from *G4PhysicsVector*. It provides, in addition, a method for the user to insert energy/value pairs in sequence. Methods to retrieve the max and min energies and values from the vector are also provided.
- *G4Timer*

  Utility class providing methods to measure elapsed user/system process time. Uses `<sys/times.h>` and `<unistd.h>` - POSIX.1.
- *G4UserLimits*

  Class collecting methods for get and set any kind of step limitation allowed in Geant4.

- *G4UnitsTable*

  Placeholder for the system of units in Geant4.

3.3. System of units

3.3.1. Basic units

Geant4 offers the user the possibility to choose and use the preferred units for any quantity. In fact, Geant4 takes care of the units. Internally a consistent set on units based on the `HepSystemOfUnits` is used:

```
millimeter             (mm)
nanosecond             (ns)
Mega electron Volt     (MeV)
positron charge        (eplus)
degree Kelvin          (kelvin)
the amount of substance (mole)
luminous intensity     (candela)
radian                 (radian)
steradian              (steradian)
```

All other units are defined from the basic ones.

For instance:

```
millimeter = mm = 1;
meter = m = 1000*mm;
...
m3 = m*m*m;
...
```

In the file `$CLHEP_BASE_DIR/include/CLHEP/Units/SystemOfUnits.h` from the CLHEP installation, one can find all untis definitions.

One can also change the system of units to be used by the kernel.

3.3.2. Input your data

3.3.2.1. Avoid 'hard coded' data

The user **must** give the units for the data to introduce:

```
G4double Size = 15*km, KineticEnergy = 90.3*GeV, density = 11*mg/cm3;
```

Geant4 assumes that these specifications for the units are respected, in order to assure indeipendence from the units chosen in the client application.

If units are not specified in the client application, data are implicitly treated in internal Geant4 system units; this practice is however strongly discouraged.

If the data set comes from an array or from an external file, it is strongly recommended to set the units as soon as the data are read, before any treatment. For instance:

```
for (int j=0, j<jmax, j++) CrossSection[j] *= millibarn;
...
my calculations
```

```
...
```

3.3.2.2. Interactive commands

Some built-in commands from the User Interface (UI) also require units to be specified.

For instance:

```
/gun/energy 15.2 keV
/gun/position 3 2 -7 meter
```

If units are not specified, or are not valid, the command is refused.

3.3.3. Output your data

You can output your data with the wished units. To do so, it is sufficient to **divide** the data by the corresponding unit:

```
G4cout << KineticEnergy/keV << " keV";
G4cout << density/(g/cm3)   << " g/cm3";
```

Of course, `G4cout << KineticEnergy` will print the energy in the internal units system.

There is another way to output the data. Let Geant4 choose the most appropriate units for the actual numerical value of the data. It is sufficient to specify to which category the data belong to (Length, Time, Energy, etc.). For example

```
G4cout << G4BestUnit(StepSize, "Length");
```

`StepSize` will be printed in km, m, mm, fermi, etc. depending of its actual value.

3.3.4. Introduce new units

If wished to introduce new units, there are two methods:

- You can complete the file `SystemOfUnits.h`

```
#include "SystemOfUnits.h"

static const G4double inch = 2.54*cm;
```

Using this method, it is not easy to define composed units. It is better to do the following:

- Instantiate an object of the class *G4UnitDefinition*

```
G4UnitDefinition ( name, symbol, category, value )
```

For example: define a few units for speed

```
G4UnitDefinition ( "km/hour" , "km/h", "Speed", km/(3600*s) );
G4UnitDefinition ( "meter/ns", "m/ns", "Speed", m/ns );
```

The category "Speed" does not exist by default in *G4UnitsTable*, but it will be created automatically. The class *G4UnitDefinition* is located in `source/global/management`.

3.3.5. Print the list of units

You can print the list of units with the static function: `G4UnitDefinition::PrintUnitsTable();`

or with the interactive command: `/units/list`

3.4. Run

3.4.1. Basic concept of *Run*

In Geant4, *Run* is the largest unit of simulation. A run consists of a sequence of events. Within a run, the detector geometry, the set up of sensitive detectors, and the physics processes used in the simulation should be kept unchanged. A run is represented by a *G4Run* class object. A run starts with `BeamOn()` method of *G4RunManager*.

3.4.1.1. Representation of a run

G4Run represents a run. It has a run identification number, which should be set by the user, and the number of events simulated during the run. Please note that the run identification number is not used by the Geant4 kernel, and thus can be arbitrarily assigned at the user's convenience.

G4Run has pointers to the tables *G4VHitsCollection* and *G4VDigiCollection*. These tables are associated in case *sensitive detectors* and *digitizer modules* are simulated, respectively. The usage of these tables will be mentioned in Section 4.4 and Section 4.5.

3.4.1.2. Manage the run procedures

G4RunManager manages the procedures of a run. In the constructor of *G4RunManager*, all of the manager classes in Geant4 kernel, except for some static managers, are constructed. These managers are deleted in the destructor of *G4RunManager*. *G4RunManager* must be a singleton, and the pointer to this singleton object can be obtained by the `getRunManager()` static method.

As already mentioned in Section 2.1, all of the *user initialization* classes and *user action* classes defined by the user should be assigned to *G4RunManager* before starting initialization of the Geant4 kernel. The assignments of these user classes are done by `SetUserInitialization()` and `SetUserAction()` methods. All user classes defined by the Geant4 kernel will be summarized in Chapter 6.

G4RunManager has several public methods, which are listed below.

`Initialize()`
: All initializations required by the Geant4 kernel are triggered by this method. Initializations are:
  - construction of the detector geometry and set up of sensitive detectors and/or digitizer modules,
  - construction of particles and physics processes,
  - calculation of cross-section tables.

  This method is thus mandatory before proceeding to the first run. This method will be invoked automatically for the second and later runs in case some of the initialized quantities need to be updated.

`BeamOn(G4int numberOfEvent)`
: This method triggers the actual simulation of a run, that is, an event loop. It takes an integer argument which represents the number of events to be simulated.

`GetRunManager()`
: This static method returns the pointer to the *G4RunManager* singleton object.

`GetCurrentEvent()`
: This method returns the pointer to the *G4Event* object which is currently being simulated. This method is available only when an event is being processed. At this moment, the application state of Geant4, which is

explained in the following sub-section, is *"EventProc"*. When Geant4 is in a state other than *"EventProc"*, this method returns `null`. Please note that the return value of this method is `const G4Event *` and thus you cannot modify the contents of the object.

`SetNumberOfEventsToBeStored(G4int nPrevious)`
When simulating the "pile up" of more than one event, it is essential to access more than one event at the same moment. By invoking this method, *G4RunManager* keeps `nPrevious G4Event` objects. This method must be invoked before proceeding to `BeamOn()`.

`GetPreviousEvent(G4int i_thPrevious)`
The pointer to the `i_thPrevious G4Event` object can be obtained through this method. A pointer to a `const` object is returned. It is inevitable that `i_thPrevious` events must have already been simulated in the same run for getting the `i_thPrevious` event. Otherwise, this method returns `null`.

`AbortRun()`
This method should be invoked whenever the processing of a run must be stopped. It is valid for *GeomClosed* and *EventProc* states. Run processing will be safely aborted even in the midst of processing an event. However, the last event of the aborted run will be incomplete and should not be used for further analysis.

3.4.1.3. *G4UserRunAction*

G4UserRunAction is one of the *user action* classes from which you can derive your own concrete class. This base class has two virtual methods, as follows:

`BeginOfRunAction()`
This method is invoked at the beginning of the `BeamOn()` method but after confirmation of the conditions of the Geant4 kernel. Likely uses of this method include:
- setting a run identification number,
- booking histograms,
- setting run specific conditions of the sensitive detectors and/or digitizer modules (e.g., dead channels).

`EndOfRunAction()`
This method is invoked at the very end of the `BeamOn()` method. Typical use cases of this method are
- store/print histograms,
- manipulate run summaries.

3.4.2. Geant4 as a state machine

Geant4 is designed as a state machine. Some methods in Geant4 are available for only a certain state(s). *G4RunManager* controls the state changes of the Geant4 application. States of Geant4 are represented by the enumeration *G4ApplicationState*. It has six states through the life cycle of a Geant4 application.

G4State_PreInit state
A Geant4 application starts with this state. The application needs to be initialized when it is in this state. The application occasionally comes back to this state if geometry, physics processes, and/or cut-off have been changed after processing a run.

G4State_Init state
The application is in this state while the `Initialize()` method of *G4RunManager* is being invoked. Methods defined in any *user initialization* classes are invoked during this state.

G4State_Idle state
The application is ready for starting a run.

G4State_GeomClosed state
When `BeamOn()` is invoked, the application proceeds to this state to process a run. Geometry, physics processes, and cut-off cannot be changed during run processing.

G4State_EventProc state
: A Geant4 application is in this state when a particular event is being processed. `GetCurrentEvent()` and `GetPreviousEvent()` methods of *G4RunManager* are available only at this state.

G4State_Quit state
: When the destructor of *G4RunManager* is invoked, the application comes to this "dead end" state. Managers of the Geant4 kernel are being deleted and thus the application cannot come back to any other state.

G4State_Abort state
: When a *G4Exception* occurs, the application comes to this "dead end" state and causes a core dump. The user still has a hook to do some "safe" opperations, e.g. storing histograms, by implementing a user concrete class of *G4VStateDependent*. The user also has a choice to suppress the occurence of *G4Exception* by a UI command */control/suppressAbortion*. When abortion is suppressed, you will still get error messages issued by G4Exception, and there is NO guarantee of a correct result after the G4Exception error message.

G4StateManager belongs to the *intercoms* category.

3.4.3. User's hook for state change

In case the user wants to do something at the moment of state change of Geant4, the user can create a concrete class of the *G4VStateDependent* base class. For example, the user can store histograms when G4Exception occurs and Geant4 comes to the *Abort* state, but before the actual core dump.

The following is an example user code which stores histograms when Geant4 becomes to the *Abort* state. This class object should be mabe in, for example *main()*, by the user code. This object will be automatically registered to *G4StateManager* at its construction.

Example 3.1. Header file of UserHookForAbortState

```
#ifndef UserHookForAbortState_H
#define UserHookForAbortState_H 1

#include "G4VStateDependent.hh"

class UserHookForAbortState : public G4VStateDependent
{
 public:
  UserHookForAbortState();   // constructor
  ~UserHookForAbortState();  // destructor

  virtual G4bool Notify(G4ApplicationState requiredState);
};
```

Example 3.2. Source file of UserHookForAbortState

```
#include "UserHookForAbortState.hh"

UserHookForAbortState::UserHookForAbortState() {;}
UserHookForAbortState::~UserHookForAbortState() {;}

G4bool UserHookForAbortState::Notify(G4ApplicationState requiredState)
{
  if(requiredState!=Abort) return true;

  // Do book keeping here

  return true;
}
```

3.4.4. Customizing the Run Manager

3.4.4.1. Virtual Methods in the Run Manager

`G4RunManager` is a concrete class with a complete set of functionalities for managing the Geant4 kernel. It is the only manager class in the Geant4 kernel which must be constructed in the `main()` method of the user's

application. Thus, instead of constructing the G4RunManager provided by Geant4, you are free to construct your own RunManager. It is recommended, however, that your RunManager inherit G4RunManager. For this purpose, G4RunManager has various virtual methods which provide all the functionalities required to handle the Geant4 kernel. Hence, your customized run manager need only override the methods particular to your needs; the remaining methods in G4RunManager base class can still be used. A summary of the available methods is presented here:

```
public: virtual void Initialize();
```
main entry point of Geant4 kernel initialization

```
protected: virtual void InitializeGeometry();
```
geometry construction

```
protected: virtual void InitializePhysics();
```
physics processes construction

```
public: virtual void BeamOn(G4int n_event);
```
main entry point of the event loop

```
protected: virtual G4bool ConfirmBeamOnCondition();
```
check the kernel conditions for the event loop

```
protected: virtual void RunInitialization();
```
prepare a run

```
protected: virtual void DoEventLoop(G4int n_events);
```
manage an event loop

```
protected: virtual G4Event* GenerateEvent(G4int i_event);
```
generation of *G4Event* object

```
protected: virtual void AnalyzeEvent(G4Event* anEvent);
```
storage/analysis of an event

```
protected: virtual void RunTermination();
```
terminate a run

```
public: virtual void DefineWorldVolume(G4VPhysicalVolume * worldVol);
```
set the world volume to *G4Navigator*

```
public: virtual void AbortRun();
```
abort the run

3.4.4.2. Customizing the Event Loop

In G4RunManager the event loop is handled by the virtual method DoEventLoop(). This method is implemented by a for loop consisting of the following steps:

1. construct a G4Event object and assign to it primary vertex(es) and primary particles. This is done by the virtual GeneratePrimaryEvent() method.
2. send the G4Event object to G4EventManager for the detector simulation. *Hits* and *trajectories* will be associated with the G4Event object as a consequence.
3. perform bookkeeping for the current G4Event object. This is done by the virtual AnalyzeEvent() method.

DoEventLoop() performs the entire simulation of an event. However, it is often useful to split the above three steps into isolated application programs. If, for example, you wish to examine the effects of changing discriminator thresholds, ADC gate widths and/or trigger conditions on simulated events, much time can be saved by performing steps 1 and 2 in one program and step 3 in another. The first program need only generate the hit/trajectory

information once and store it, perhaps in a database. The second program could then retrieve the stored `G4Event` objects and perform the digitization (analysis) using the above threshold, gate and trigger settings. These settings could then be changed and the digitization program re-run without re-generating the `G4Event`s.

3.4.4.3. Changing the Detector Geometry

The detector geometry defined in your *G4VUserDetectorConstruction* concrete class can be changed during a run break (between two runs). Two different cases are considered.

The first is the case in which you want to delete the entire structure of your old geometry and build up a completely new set of volumes. For this case, you need to set the new world physical volume pointer to the *RunManager*. Thus, you should proceed in the following way.

```
G4RunManager* runManager = G4RunManager::GetRunManager();
runManager->DefineWorldVolume( newWorldPhys );
```

Presumably this case is rather rare. The second case is more frequent for the user.

The second case is the following. Suppose you want to move and/or rotate a particular piece of your detector component. This case can easily happen for a beam test of your detector. It is obvious for this case that you need not change the world volume. Rather, it should be said that your world volume (experimental hall for your beam test) should be big enough for moving/rotating your test detector. For this case, you can still use all of your detector geometries, and just use a `Set` method of a particular physical volume to update the transformation vector as you want. Thus, you don't need to re-set your world volume pointer to *RunManager*.

If you want to change your geometry for every run, you can implement it in the `BeginOfRunAction()` method of *G4UserRunAction* class, which will be invoked at the beginning of each run, or, derive the `RunInitialization()` method. Please note that, for both of the above mentioned cases, you need to let *RunManager* know "the geometry needs to be closed again". Thus, you need to invoke

```
runManager->GeometryHasBeenModified();
```

before proceeding to the next run. An example of changing geometry is given in a Geant4 tutorial in Geant4 Training kit #2.

3.4.4.4. Switch physics processes

In the `InitializePhysics()` method, `G4VUserPhysicsList::Construct` is invoked in order to define particles and physics processes in your application. Basically, you can not add nor remove any particles during execution, because particles are static objects in Geant4 (see Section 2.4 and Section 5.3 for details). In addition, it is very difficult to add and/or remove physics processes during execution, because registration procedures are very complex, except for experts (see Section 2.5 and Section 5.2). This is why the `initializePhysics()` method is assumed to be invoked at once in Geant4 kernel initialization.

However, you can switch on/off physics processes defined in your *G4VUserPhysicsList* concrete class and also change parameters in physics processes during the run break.

You can use `ActivateProcess()` and `InActivateProcess()` methods of *G4ProcessManager* anywhere outside the event loop to switch on/off some process. You should be very careful to switch on/off processes inside the event loop, though it is not prohibited to use these methods even in the *EventProc* state.

It is a likely case to change cut-off values in a run. You can change `defaultCutValue` in *G4VUserPhysicsList* during the *Idle* state. In this case, all cross section tables need to be recalculated before the event loop. You should use the `CutOffHasBeenModified()` method when you change cut-off values so that the `SetCuts` method of your *PhysicsList* concrete class will be invoked.

3.5. Event

3.5.1. Representation of an event

G4Event represents an event. An object of this class contains all inputs and outputs of the simulated event. This class object is constructed in *G4RunManager* and sent to *G4EventManager*. The event currently being processed can be obtained via the `getCurrentEvent()` method of *G4RunManager*.

3.5.2. Structure of an event

A *G4Event* object has four major types of information. Get methods for this information are available in *G4Event*.

Primary vertexes and primary particles
: Details are given in Section 3.6.

Trajectories
: Trajectories are stored in G4TrajectoryContainer class objects and the pointer to this container is stored in *G4Event*. The contents of a trajectory are given in Section 5.1.6.

Hits collections
: Collections of hits generated by *sensitive detectors* are kept in *G4HCofThisEvent* class object and the pointer to this container class object is stored in *G4Event*. See Section 4.4 for the details.

Digits collections
: Collections of digits generated by *digitizer modules* are kept in *G4DCofThisEvent* class object and the pointer to this container class object is stored in *G4Event*. See Section 4.5 for the details.

3.5.3. Mandates of *G4EventManager*

G4EventManager is the manager class to take care of one event. It is responsible for:

- converting *G4PrimaryVertex* and *G4PrimaryParticle* objects associated with the current *G4Event* object to *G4Track* objects. All of *G4Track* objects representing the primary particles are sent to *G4StackManager*.
- Pop one *G4Track* object from *G4StackManager* and send it to *G4TrackingManager*. The current *G4Track* object is deleted by *G4EventManager* after the track is simulated by *G4TrackingManager*, if the track is marked as "killed".
- In case the primary track is "suspended" or "postponed to next event" by *G4TrackingManager*, it is sent back to the *G4StackManager*. Secondary *G4Track* objects returned by *G4TrackingManager* are also sent to *G4StackManager*.
- When *G4StackManager* returns `NULL` for the "pop" request, *G4EventManager* terminates the current processing event.
- invokes the user-defined methods `beginOfEventAction()` and `endOfEventAction()` from the *G4UserEventAction* class. See Section 6.3 for details.

3.5.4. Stacking mechanism

G4StackManager has three stacks, named *urgent*, *waiting* and *postpone-to-next-event*, which are objects of the *G4TrackStack* class. By default, all *G4Track* objects are stored in the *urgent* stack and handled in a "last in first out" manner. In this case, the other two stacks are not used. However, tracks may be routed to the other two stacks by the user-defined *G4UserStackingAction* concrete class.

If the methods of *G4UserStackingAction* have been overridden by the user, the *postpone-to-next-event* and *waiting* stacks may contain tracks. At the beginning of an event, *G4StackManager* checks to see if any tracks left over from the previous event are stored in the *postpone-to-next-event stack*. If so, it attemps to move them to the *urgent* stack. But first the `PrepareNewEvent()` method of *G4UserStackingAction* is called. Here tracks may be re-classified by the user and sent to the *urgent* or *waiting* stacks, or deferred again to the *postpone-to-next-event* stack.

As the event is processed *G4StackManager* pops tracks from the *urgent* stack until it is empty. At this point the `NewStage()` method of *G4UserStackingAction* is called. In this method tracks from the *waiting* stack may be sent to the *urgent* stack, retained in the *waiting* stack or postponed to the next event.

Details of the user-defined methods of *G4UserStackingAction* and how they affect track stack management are given in Section 6.3.

3.6. Event Generator Interface

3.6.1. Structure of a primary event

3.6.1.1. Primary vertex and primary particle

The *G4Event* class object should have a set of primary particles when it is sent to *G4EventManager* via `processOneEvent()` method. It is the mandate of your *G4VUserPrimaryGeneratorAction* concrete class to send primary particles to the *G4Event* object.

The *G4PrimaryParticle* class represents a primary particle with which Geant4 starts simulating an event. This class object has information on particle type and its three momenta. The positional and time information of primary particle(s) are stored in the *G4PrimaryVertex* class object and, thus, this class object can have one or more *G4PrimaryParticle* class objects which share the same vertex. Primary vertexes and primary particles are associated with the *G4Event* object by a form of linked list.

A concrete class of *G4VPrimaryGenerator*, the *G4PrimaryParticle* object is constructed with either a pointer to *G4ParticleDefinition* or an integer number which represents P.D.G. particle code. For the case of some artificial particles, e.g., geantino, optical photon, etc., or exotic nuclear fragments, which the P.D.G. particle code does not cover, the *G4PrimaryParticle* should be constructed by *G4ParticleDefinition* pointer. On the other hand, elementary particles with very short life time, e.g., weak bosons, or quarks/gluons, can be instantiated as *G4PrimaryParticle* objects using the P.D.G. particle code. It should be noted that, even though primary particles with such a very short life time are defined, Geant4 will simulate only the particles which are defined as *G4ParticleDefinition* class objects. Other primary particles will be simply ignored by *G4EventManager*. But it may still be useful to construct such "intermediate" particles for recording the origin of the primary event.

3.6.1.2. Forced decay channel

The *G4PrimaryParticle* class object can have a list of its daughter particles. If the parent particle is an "intermediate" particle, which Geant4 does not have a corresponding *G4ParticleDefinition*, this parent particle is ignored and daughters are assumed to start from the vertex with which their parent is associated. For example, a Z boson is associated with a vertex and it has positive and negative muons as its daughters, these muons will start from that vertex.

There are some kinds of particles which should fly some reasonable distances and, thus, should be simulated by Geant4, but you still want to follow the decay channel generated by an event generator. A typical case of these particles is B meson. Even for the case of a primary particle which has a corresponding *G4ParticleDefinition*, it can have daughter primary particles. Geant4 will trace the parent particle until it comes to decay, obeying multiple scattering, ionization loss, rotation with the magnetic field, etc. according to its particle type. When the parent comes to decay, instead of randomly choosing its decay channel, it follows the "pre-assigned" decay channel. To conserve the energy and the momentum of the parent, daughters will be Lorentz transformed according to their parent's frame.

3.6.2. Interface to a primary generator

3.6.2.1. G4HEPEvtInterface

Unfortunately, almost all event generators presently in use, commonly are written in FORTRAN. For Geant4, it was decided to not link with any FORTRAN program or library, even though the C++ language syntax itself

allows such a link. Linking to a FORTRAN package might be convenient in some cases, but we will lose many advantages of object-oriented features of C++, such as robustness. Instead, Geant4 provides an ASCII file interface for such event generators.

G4HEPEvtInterface is one of *G4VPrimaryGenerator* concrete class and thus it can be used in your *G4VUserPrimaryGeneratorAction* concrete class. *G4HEPEvtInterface* reads an ASCII file produced by an event generator and reproduces *G4PrimaryParticle* objects associated with a *G4PrimaryVertex* object. It reproduces a full production chain of the event generator, starting with primary quarks, etc. In other words, *G4HEPEvtInterface* converts information stored in the `/HEPEVT/` common block to an object-oriented data structure. Because the `/HEPEVT/` common block is commonly used by almost all event generators written in FORTRAN, *G4HEPEvtInterface* can interface to almost all event generators currently used in the HEP community. The constructor of *G4HEPEvtInterface* takes the file name. Example 3.3 shows an example how to use *G4HEPEvtInterface*. Note that an event generator is not assumed to give a place of the primary particles, the interaction point must be set before invoking *GeneratePrimaryVertex()* method.

Example 3.3. An example code for *G4HEPEvtInterface*

```
#ifndef ExN04PrimaryGeneratorAction_h
#define ExN04PrimaryGeneratorAction_h 1

#include "G4VUserPrimaryGeneratorAction.hh"
#include "globals.hh"

class G4VPrimaryGenerator;
class G4Event;

class ExN04PrimaryGeneratorAction : public G4VUserPrimaryGeneratorAction
{
  public:
    ExN04PrimaryGeneratorAction();
    ~ExN04PrimaryGeneratorAction();

  public:
    void GeneratePrimaries(G4Event* anEvent);

  private:
    G4VPrimaryGenerator* HEPEvt;
};

#endif


#include "ExN04PrimaryGeneratorAction.hh"

#include "G4Event.hh"
#include "G4HEPEvtInterface.hh"

ExN04PrimaryGeneratorAction::ExN04PrimaryGeneratorAction()
{
  HEPEvt = new G4HEPEvtInterface("pythia_event.data");
}

ExN04PrimaryGeneratorAction::~ExN04PrimaryGeneratorAction()
{
  delete HEPEvt;
}

void ExN04PrimaryGeneratorAction::GeneratePrimaries(G4Event* anEvent)
{
  HEPEvt->SetParticlePosition(G4ThreeVector(0.*cm,0.*cm,0.*cm));
  HEPEvt->GeneratePrimaryVertex(anEvent);
}
```

3.6.2.2. Format of the ASCII file

An ASCII file, which will be fed by *G4HEPEvtInterface* should have the following format.

- The first line of each primary event should be an integer which represents the number of the following lines of primary particles.

- Each line in an event corresponds to a particle in the `/HEPEVT/` common. Each line has `ISTHEP, IDHEP, JDAHEP(1), JDAHEP(2), PHEP(1), PHEP(2), PHEP(3), PHEP(5).` Refer to the `/HEPEVT/` manual for the meanings of these variables.

Example 3.4 shows an example FORTRAN code to generate an ASCII file.

Example 3.4. A FORTRAN example using the `/HEPEVT/` common.

```
*********************************************************
      SUBROUTINE HEP2G4
*
* Convert /HEPEVT/ event structure to an ASCII file
* to be fed by G4HEPEvtInterface
*
*********************************************************
      PARAMETER (NMXHEP=2000)
      COMMON/HEPEVT/NEVHEP,NHEP,ISTHEP(NMXHEP),IDHEP(NMXHEP),
     >JMOHEP(2,NMXHEP),JDAHEP(2,NMXHEP),PHEP(5,NMXHEP),VHEP(4,NMXHEP)
      DOUBLE PRECISION PHEP,VHEP
*
      WRITE(6,*) NHEP
      DO IHEP=1,NHEP
       WRITE(6,10)
     >  ISTHEP(IHEP),IDHEP(IHEP),JDAHEP(1,IHEP),JDAHEP(2,IHEP),
     >  PHEP(1,IHEP),PHEP(2,IHEP),PHEP(3,IHEP),PHEP(5,IHEP)
10     FORMAT(4I10,4(1X,D15.8))
      ENDDO
*
      RETURN
      END
```

3.6.2.3. Future interface to the new generation generators

Several activities have already been started for developing object-oriented event generators. Such new generators can be easily linked and used with a Geant4 based simulation. Furthermore, we need not distinguish a primary generator from the physics processes used in Geant4. Future generators can be a kind of physics process plugged-in by inheriting *G4VProcess*.

3.6.3. Event overlap using multiple generators

Your *G4VUserPrimaryGeneratorAction* concrete class can have more than one *G4VPrimaryGenerator* concrete class. Each *G4VPrimaryGenerator* concrete class can be accessed more than once per event. Using these class objects, one event can have more than one primary event.

One possible use is the following. Within an event, a *G4HEPEvtInterface* class object instantiated with a minimum bias event file is accessed 20 times and another *G4HEPEvtInterface* class object instantiated with a signal event file is accessed once. Thus, this event represents a typical signal event of LHC overlapping 20 minimum bias events. It should be noted that a simulation of event overlapping can be done by merging hits and/or digits associated with several events, and these events can be simulated independently. Digitization over multiple events will be mentioned in Section 4.5.

3.7. Event Biasing Techniques

3.7.1. Scoring, Geometrical Importance Sampling and Weight Roulette

Geant4 provides event biasing techniques which may be used to save computing time in such applications as the simulation of radiation shielding. These are *geometrical splitting* and *Russian roulette* (also called geometrical importance sampling), and *weight roulette*. Scoring is carried out by *G4MultiFunctionalDetector* (see Section 4.4.5 and Section 4.4.6) using the standard Geant4 scoring technique. Biasing specific scorers have been implemented and are described within *G4MultiFunctionDetector* documentation. In this chapter, it is assumed that the reader is familiar with both the usage of Geant4 and the concepts of importance sampling. More detailed documentation

may be found in the documents 'Scoring, geometrical importance sampling and weight roulette' . A detailed description of different use-cases which employ the sampling and scoring techniques can be found in the document 'Use cases of importance sampling and scoring in Geant4' .

The purpose of importance sampling is to save computing time by sampling less often the particle histories entering "less important" geometry regions, and more often in more "important" regions. Given the same amount of computing time, an importance-sampled and an analogue-sampled simulation must show equal mean values, while the importance-sampled simulation will have a decreased variance.

The implementation of scoring is independent of the implementation of importance sampling. However both share common concepts. *Scoring and importance sampling apply to particle types chosen by the user*, which should be borne in mind when interpreting the output of any biased simulation.

Examples on how to use scoring and importance sampling may be found in `examples/extended/biasing`.

3.7.1.1. Geometries

The kind of scoring referred to in this note and the importance sampling apply to spatial cells provided by the user.

A **cell** is a physical volume (further specified by it's replica number, if the volume is a replica). Cells may be defined in two kinds of geometries:

1. **mass geometry**: the geometry setup of the experiment to be simulated. Physics processes apply to this geometry.
2. **parallel-geometry**: a geometry constructed to define the physical volumes according to which scoring and/or importance sampling is applied.

The user has the choice to score and/or sample by importance the particles of the chosen type, according to mass geometry or to parallel geometry. It is possible to utilize several parallel geometries in addition to the mass geometry. This provides the user with a lot of flexibility to define separate geometries for different particle types in order to apply scoring or/and importance sampling.

Note

Parallel geometries should be constructed using the implementation as described in Section 4.7. There are a few conditions for parallel geometries:

- The world volume for parallel and mass geometries must be identical copies.
- Scoring and importance cells must not share boundaries with the world volume.

3.7.1.2. Changing the Sampling

Samplers are higher level tools which perform the necessary changes of the Geant4 sampling in order to apply importance sampling and weight roulette.

Variance reduction (and scoring through the *G4MultiFunctionalDetector*) may be combined arbitrarily for chosen particle types and may be applied to the mass or to parallel geometries.

The `G4GeometrySampler` can be applied equally to mass or parallel geometries with an abstract interface supplied by `G4VSampler`. `G4VSampler` provides `Prepare...` methods and a `Configure` method:

```
class G4VSampler
{
  public:
   G4VSampler();
   virtual ~G4VSampler();
   virtual void PrepareImportanceSampling(G4VIStore *istore,
                                          const G4VImportanceAlgorithm
                                          *ialg = 0) = 0;
   virtual void PrepareWeightRoulett(G4double wsurvive = 0.5,
                                     G4double wlimit = 0.25,
                                     G4double isource = 1) = 0;
   virtual void PrepareWeightWindow(G4VWeightWindowStore *wwstore,
```

```
                                    G4VWeightWindowAlgorithm *wwAlg = 0,
                                    G4PlaceOfAction placeOfAction =
                                    onBoundary) = 0;
   virtual void Configure() = 0;
   virtual void ClearSampling() = 0;
   virtual G4bool IsConfigured() const = 0;
};
```

The methods for setting up the desired combination need specific information:

- Importance sampling: message `PrepareImportanceSampling` with a `G4VIStore` and optionally a `G4VImportanceAlgorithm`
- Weight window: message `PrepareWeightWindow` with the arguments:
  - **wwstore*: a `G4VWeightWindowStore` for retrieving the lower weight bounds for the energy-space cells
  - **wwAlg*: a `G4VWeightWindowAlgorithm` if a customized algorithm should be used
  - *placeOfAction*: a `G4PlaceOfAction` specifying where to perform the biasing
- Weight roulette: message `PrepareWeightRoulett` with the optional parameters:
  - *wsurvive*: survival weight
  - *wlimit*: minimal allowed value of weight * source importance / cell importance
  - *isource*: importance of the source cell

Each object of a sampler class is responsible for one particle type. The particle type is given to the constructor of the sampler classes via the particle type name, e.g. "neutron". Depending on the specific purpose, the `Configure()` of a sampler will set up specialized processes (derived from `G4VProcess`) for transportation in the parallel geometry, importance sampling and weight roulette for the given particle type. When `Configure()` is invoked the sampler places the processes in the correct order independent of the order in which user invoked the `Prepare...` methods.

Note

- The `Prepare...()` functions may each only be invoked once.
- To configure the sampling the function `Configure()` must be called *after* the `G4RunManager` has been initialized and the PhysicsList has been instantiated.

The interface and framework are demonstrated in the `examples/extended/biasing` directory, with the main changes being to the G4GeometrySampler class and the fact that in the parallel case the WorldVolume is a copy of the Mass World. The parallel geometry now has to inherit from *G4VUserParallelWorld* which also has the *GetWorld()* method in order to retrieve a copy of the mass geometry WorldVolume.

```
class B02ImportanceDetectorConstruction : public G4VUserParallelWorld
ghostWorld = GetWorld();
```

The constructor for *G4GeometrySampler* takes a pointer to the physical world volume and the particle type name (e.g. "neutron") as arguments. In a single mass geometry the sampler is created as follows:

```
G4GeometrySampler mgs(detector->GetWorldVolume(),"neutron");
mgs.SetParallel(false);
```

Whilst the following lines of code are required in order to set up the sampler for the parallel geometry case:

```
G4VPhysicalVolume* ghostWorld = pdet->GetWorldVolume();

G4GeometrySampler pgs(ghostWorld,"neutron");

pgs.SetParallel(true);
```

Also note that the preparation and configuration of the samplers has to be carried out *after* the instantiation of the UserPhysicsList and after the initialisation of the *G4RunManager*:

```
pgs.PrepareImportanceSampling(&aIstore, 0);
pgs.Configure();
```

Due to the fact that biasing is a process and has to be inserted after all the other processes have been created.

3.7.1.3. Importance Sampling

Importance sampling acts on particles crossing boundaries between "importance cells". The action taken depends on the importance values assigned to the cells. In general a particle history is either split or Russian roulette is played if the importance increases or decreases, respectively. A weight assigned to the history is changed according to the action taken.

The tools provided for importance sampling require the user to have a good understanding of the physics in the problem. This is because the user has to decide which particle types require importance sampled, define the cells, and assign importance values to the cells. If this is not done properly the results cannot be expected to describe a real experiment.

The assignment of importance values to a cell is done using an importance store described below.

An "importance store" with the interface `G4VIStore` is used to store importance values related to cells. In order to do importance sampling the user has to create an object (e.g. of class `G4IStore`) of type `G4VIStore`. The samplers may be given a `G4VIStore`. The user fills the store with cells and their importance values.

An importance store has to be constructed with a reference to the world volume of the geometry used for importance sampling. This may be the world volume of the mass or of a parallel geometry. Importance stores derive from the interface `G4VIStore`:

```
class  G4VIStore
{
  public:
    G4VIStore();
    virtual  ~G4VIStore();
    virtual G4double GetImportance(const G4GeometryCell &gCell) const = 0;
    virtual G4bool IsKnown(const G4GeometryCell &gCell) const = 0;
    virtual const G4VPhysicalVolume &GetWorldVolume() const = 0;
};
```

A concrete implementation of an importance store is provided by the class `G4VStore`. The *public* part of the class is:

```
class G4IStore : public G4VIStore
{
  public:
    explicit G4IStore(const G4VPhysicalVolume &worldvolume);
    virtual ~G4IStore();
    virtual G4double GetImportance(const G4GeometryCell &gCell) const;
    virtual G4bool IsKnown(const G4GeometryCell &gCell) const;
    virtual const G4VPhysicalVolume &GetWorldVolume() const;
    void AddImportanceGeometryCell(G4double importance,
                              const G4GeometryCell &gCell);
    void AddImportanceGeometryCell(G4double importance,
                              const G4VPhysicalVolume &,
                                    G4int aRepNum = 0);
    void ChangeImportance(G4double importance,
                          const G4GeometryCell &gCell);
    void ChangeImportance(G4double importance,
                          const G4VPhysicalVolume &,
                              G4int aRepNum = 0);
    G4double GetImportance(const G4VPhysicalVolume &,
                               G4int aRepNum = 0) const ;
  private: .....
};
```

The member function `AddImportanceGeometryCell()` enters a cell and an importance value into the importance store. The importance values may be returned either according to a physical volume and a replica number or according to a `G4GeometryCell`. The user must be aware of the interpretation of assigning importance values to a cell. If scoring is also implemented then this is attached to logical volumes, in which case the physical volume and replica number method should be used for assigning importance values. See `examples/extended/biasing B01` and `B02` for examples of this.

Note

- An importance value must be assigned to every cell.

The different cases:

- *Cell is not in store*

  Not filling a certain cell in the store will cause an exception.
- *Importance value = zero*

  Tracks of the chosen particle type will be killed.
- *importance values > 0*

  Normal allowed values
- *Importance value smaller zero*

  Not allowed!

3.7.1.4. The Importance Sampling Algorithm

Importance sampling supports using a customized importance sampling algorithm. To this end, the sampler interface `G4VSampler` may be given a pointer to the interface `G4VImportanceAlgorithm`:

```
class G4VImportanceAlgorithm
{
  public:
    G4VImportanceAlgorithm();
    virtual ~G4VImportanceAlgorithm();
    virtual G4Nsplit_Weight Calculate(G4double ipre,
                                      G4double ipost,
                                      G4double init_w) const = 0;
};
```

The method `Calculate()` takes the arguments:

- *ipre*, *ipost*: importance of the previous cell and the importance of the current cell, respectively.
- *init_w*: the particles weight

It returns the struct:

```
class G4Nsplit_Weight
{
  public:

  G4int fN;
  G4double fW;
};
```

- *fN*: the calculated number of particles to exit the importance sampling
- *fW*: the weight of the particles

The user may have a customized algorithm used by providing a class inheriting from `G4VImportanceAlgorithm`.

If no customized algorithm is given to the sampler the default importance sampling algorithm is used. This algorithm is implemented in `G4ImportanceAlgorithm`.

3.7.1.5. The Weight Window Technique

The weight window technique is a weight-based alternative to importance sampling:

- applies splitting and Russian roulette depending on space (cells) and energy

- user defines weight windows in contrast to defining importance values as in importance sampling

In contrast to importance sampling this technique is not weight blind. Instead the technique is applied according to the particle weight with respect to the current energy-space cell.

Therefore the technique is convenient to apply in combination with other variance reduction techniques such as cross-section biasing and implicit capture.

A weight window may be specified for every cell and for several energy regions: *space-energy cell*.

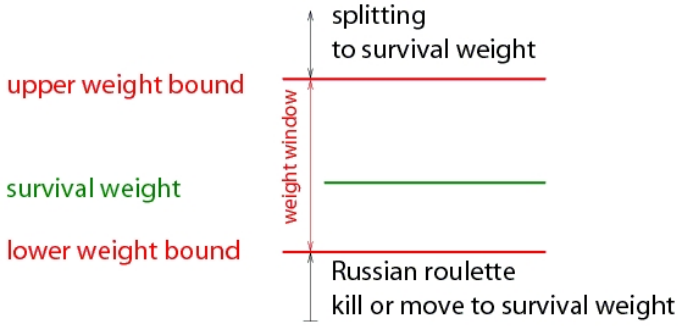


Figure 3.2. Weight window concept

Weight window concept

The user specifies a *lower weight bound W_L* for every space-energy cell.

- The upper weight bound W_U and the survival weight W_S are calculated as:

  W_U = C_U *W_L* and

  W_S = C_S *W_L*.
- The user specifies C_S and C_U once for the whole problem.
- The user may give different sets of energy bounds for every cell or one set for all geometrical cells
- Special case: if C_S = C_U = 1 for all energies then weight window is equivalent to importance sampling
- The user can choose to apply the technique: at boundaries, on collisions or on boundaries and collisions

The energy-space cells are realized by `G4GeometryCell` as in importance sampling. The cells are stored in a weight window store defined by `G4VWeightWindowStore`:

```
class  G4VWeightWindowStore {
 public:
   G4VWeightWindowStore();
   virtual  ~G4VWeightWindowStore();
   virtual G4double GetLowerWeitgh(const G4GeometryCell &gCell,
                                   G4double partEnergy) const = 0;
   virtual G4bool IsKnown(const G4GeometryCell &gCell) const = 0;
   virtual const G4VPhysicalVolume &GetWorldVolume() const = 0;
};
```

A concrete implementation is provided:

```
 class G4WeightWindowStore: public G4VWeightWindowStore {
  public:
    explicit G4WeightWindowStore(const G4VPhysicalVolume &worldvolume);
    virtual ~G4WeightWindowStore();
    virtual G4double GetLowerWeitgh(const G4GeometryCell &gCell,
                                    G4double partEnergy) const;
    virtual G4bool IsKnown(const G4GeometryCell &gCell) const;
    virtual const G4VPhysicalVolume &GetWorldVolume() const;
    void AddLowerWeights(const G4GeometryCell &gCell,
                         const std::vector<G4double> &lowerWeights);
```

```
    void AddUpperEboundLowerWeightPairs(const G4GeometryCell &gCell,
                                        const G4UpperEnergyToLowerWeightMap&
                                        enWeMap);
    void SetGeneralUpperEnergyBounds(const
        std::set<G4double, std::less<G4double> > & enBounds);

  private::
  ...
 };
```

The user may choose equal energy bounds for all cells. In this case a set of upper energy bounds must be given to the store using the method `SetGeneralUpperEnergyBounds`. If a general set of energy bounds have been set `AddLowerWeights` can be used to add the cells.

Alternatively, the user may chose different energy regions for different cells. In this case the user must provide a mapping of upper energy bounds to lower weight bounds for every cell using the method `AddUpperEbound-LowerWeightPairs`.

Weight window algorithms implementing the interface class `G4VWeightWindowAlgorithm` can be used to define a customized algorithm:

```
class G4VWeightWindowAlgorithm {
 public:
   G4VWeightWindowAlgorithm();
   virtual ~G4VWeightWindowAlgorithm();
   virtual G4Nsplit_Weight Calculate(G4double init_w,
                                     G4double lowerWeightBound) const = 0;
};
```

A concrete implementation is provided and used as a default:

```
class G4WeightWindowAlgorithm : public G4VWeightWindowAlgorithm {
 public:
   G4WeightWindowAlgorithm(G4double upperLimitFaktor = 5,
                           G4double survivalFaktor = 3,
                           G4int maxNumberOfSplits = 5);
   virtual ~G4WeightWindowAlgorithm();
   virtual G4Nsplit_Weight Calculate(G4double init_w,
                                     G4double lowerWeightBound) const;
 private:
  ...
};
```

The constructor takes three parameters which are used to: calculate the upper weight bound (upperLimitFaktor), calculate the survival weight (survivalFaktor), and introduce a maximal number (maxNumberOfSplits) of copies to be created in one go.

In addition, the inverse of the maxNumberOfSplits is used to specify the minimum survival probability in case of Russian roulette.

3.7.1.6. The Weight Roulette Technique

Weight roulette (also called weight cutoff) is usually applied if importance sampling and implicit capture are used together. Implicit capture is not described here but it is useful to note that this procedure reduces a particle weight in every collision instead of killing the particle with some probability.

Together with importance sampling the weight of a particle may become so low that it does not change any result significantly. Hence tracking a very low weight particle is a waste of computing time. Weight roulette is applied in order to solve this problem.

The weight roulette concept

Weight roulette takes into account the importance "Ic" of the current cell and the importance "Is" of the cell in which the source is located, by using the ratio "R=Is/Ic".

Weight roulette uses a relative minimal weight limit and a relative survival weight. When a particle falls below the weight limit Russian roulette is applied. If the particle survives, tracking will be continued and the particle weight will be set to the survival weight.

The weight roulette uses the following parameters with their default values:

- *wsurvival*: 0.5
- *wlimit*: 0.25
- *isource*: 1

The following algorithm is applied:

If a particle weight "w" is lower than R*wlimit:

- the weight of the particle will be changed to "ws = wsurvival*R"
- the probability for the particle to survive is "p = w/ws"

3.7.2. Physics Based Biasing

Geant4 supports physics based biasing through a number of general use, built in biasing techniques. A utility class, G4WrapperProcess, is also available to support user defined biasing.

3.7.2.1. Built in Biasing Options

3.7.2.1.1. Primary Particle Biasing

Primary particle biasing can be used to increase the number of primary particles generated in a particular phase space region of interest. The weight of the primary particle is modified as appropriate. A general implementation is provided through the G4GeneralParticleSource class. It is possible to bias position, angular and energy distributions.

G4GeneralParticleSource is a concrete implementation of G4VPrimaryGenerator. To use, instantiate G4GeneralParticleSource in the G4VUserPrimaryGeneratorAction class, as demonstrated below.

```
MyPrimaryGeneratorAction::MyPrimaryGeneratorAction() {
   generator = new G4GeneralParticleSource;
}

void
MyPrimaryGeneratorAction::GeneratePrimaries(G4Event*anEvent){
   generator->GeneratePrimaryVertex(anEvent);
}
```

The biasing can be configured through interactive commands. Extensive documentation can be found in Primary particle biasing. Examples are also distributed with the Geant4 distribution in **examples/extended/eventgenerator/exgps**.

3.7.2.1.2. Radioactive Decay Biasing

The G4RadioactiveDecay class simulates the decay of radioactive nuclei and implements the following biasing options:

- Increase the sampling rate of radionuclides within observation times through a user defined probability distribution function
- Nuclear splitting, where the parent nuclide is split into a user defined number of nuclides
- Branching ratio biasing where branching ratios are sampled with equal probability

G4RadioactiveDecay is a process which must be registered with a process manager, as demonstrated below.

```
void MyPhysicsList::ConstructProcess()
{
```

```
    ...
    G4RadioactiveDecay* theRadioactiveDecay =
       new  G4RadioactiveDecay();

    G4ProcessManager* pmanager = ...
    pmanager ->AddProcess(theRadioactiveDecay);
    ...
}
```

The biasing can be controlled either in compiled code or through interactive commands. Extensive documentation can be found in Radioactive decay biasing example and Radioactive decay biasing .

Radioactive decay biasing examples are also distributed with the Geant4 distribution in **examples/extended/radioactivedecay/exrdm**.

3.7.2.1.3. Hadronic Leading Particle Biasing

One hadronic leading particle biasing technique is implemented in the G4HadLeadBias utility. This method keeps only the most important part of the event, as well as representative tracks of each given particle type. So the track with the highest energy as well as one of each of Baryon, pi0, mesons and leptons. As usual, appropriate weights are assigned to the particles. Setting the **SwitchLeadBiasOn** environmental variable will activate this utility.

3.7.2.1.4. Hadronic Cross Section Biasing

Cross section biasing artificially enhances/reduces the cross section of a process. This may be useful for studying thin layer interactions or thick layer shielding. The built in hadronic cross section biasing applies to photon inelastic, electron nuclear and positron nuclear processes.

The biasing is controlled through the **BiasCrossSectionByFactor** method in G4HadronicProcess, as demonstrated below.

```
void MyPhysicsList::ConstructProcess()
{
   ...
   G4ElectroNuclearReaction * theElectroReaction =
      new G4ElectroNuclearReaction;

   G4ElectronNuclearProcess theElectronNuclearProcess;
   theElectronNuclearProcess.RegisterMe(theElectroReaction);
   theElectronNuclearProcess.BiasCrossSectionByFactor(100);

   pManager->AddDiscreteProcess(&theElectronNuclearProcess);
   ...
}
```

3.7.2.2. G4WrapperProcess

G4WrapperProcess can be used to implement user defined event biasing. G4WrapperProcess, which is a process itself, wraps an existing process. By default, all function calls are forwared to the wrapped process. It is a non-invasive way to modify the behaviour of an existing process.

To use this utility, first create a derived class inheriting from G4WrapperProcess. Override the methods whose behaviour you would like to modify, for example, PostStepDoIt, and register the derived class in place of the process to be wrapped. Finally, register the wrapped process with G4WrapperProcess. The code snippets below demonstrate its use.

```
class MyWrapperProcess  : public G4WrapperProcess {
...
 G4VParticleChange* PostStepDoIt(const G4Track& track,
                                 const G4Step& step) {
    // Do something interesting
 }
};


void MyPhysicsList::ConstructProcess()
```

```
{
...
   G4LowEnergyBremsstrahlung* bremProcess =
      new G4LowEnergyBremsstrahlung();

   MyWrapperProcess* wrapper = new MyWrapperProcess();
   wrapper->RegisterProcess(bremProcess);

   processManager->AddProcess(wrapper, -1, -1, 3);
}
```

3.7.3. Adjoint/Reverse Monte Carlo

Another powerful biasing technique available in Geant4 is the Reverse Monte Carlo (RMC) method, also known as the Adjoint Monte Carlo method. In this method particles are generated on the external boundary of the sensitive part of the geometry and then are tracked backward in the geometry till they reach the external source surface, or exceed an energy threshold. By this way the computing time is focused only on particle tracks that are contributing to the tallies. The RMC method is much rapid than the Forward MC method when the sensitive part of the geometry is small compared to the rest of the geometry and to the external source, that has to be extensive and not beam like. At the moment the RMC method is implemented in Geant4 only for some electromagnetic processes (see Section 3.7.3.1.3). An example illustrating the use of the Reverse MC method in Geant4 is distributed within the Geant4 toolkit in **examples/extended/biasing/ReverseMC01**.

3.7.3.1. Treatment of the Reverse MC method in Geant4

Different G4Adjoint classes have been implemented into the Geant4 toolkit in order to run an adjoint/reverse simulation in a Geant4 application. This implementation is illustrated in Figure 3.3. An adjoint run is divided in a serie of alternative adjoint and forward tracking of adjoint and normal particles. One Geant4 event treats one of this tracking phase.

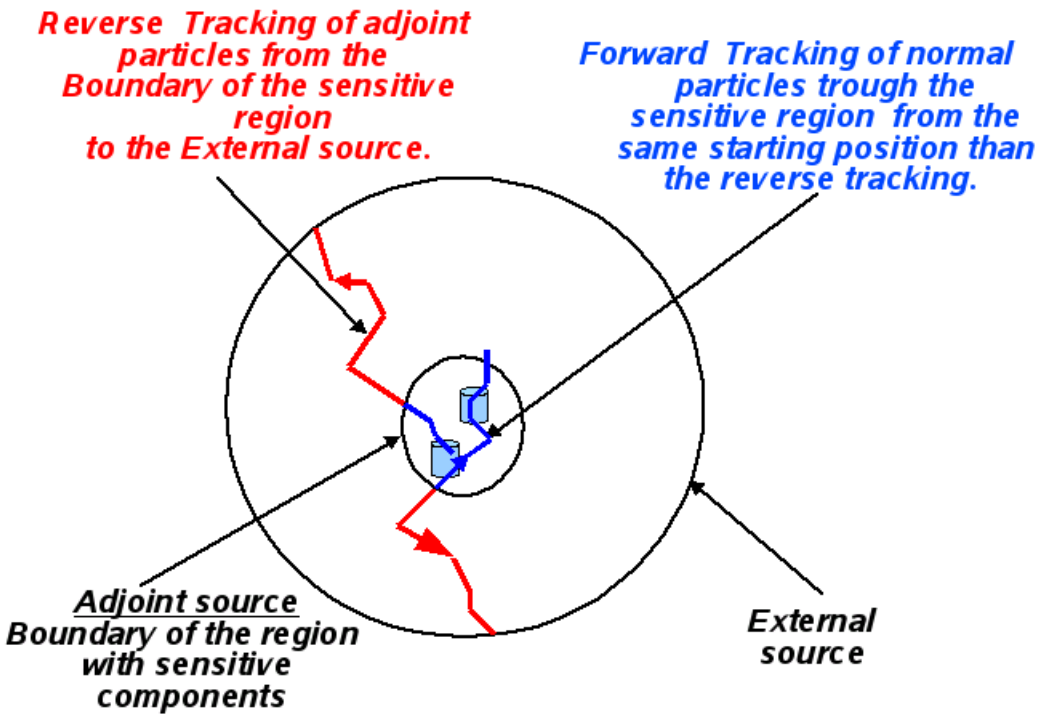

Reverse Tracking of adjoint particles from the Boundary of the sensitive region to the External source.
Forward Tracking of normal particles trough the sensitive region from the same starting position than the reverse tracking.
Adjoint source
Boundary of the region with sensitive components
External source

Figure 3.3. Schematic view of an adjoint/reverse simulation in Geant4

3.7.3.1.1. Adjoint tracking phase

Adjoint particles (adjoint_e-, adjoint_gamma,...) are generated one by one on the so called adjoint source with random position, energy (1/E distribution) and direction. The adjoint source is the external surface of a user defined

volume or of a user defined sphere. The adjoint source should contain one or several sensitive volumes and should be small compared to the entire geometry. The user can set the minimum and maximum energy of the adjoint source. After its generation the adjoint primary particle is tracked backward in the geometry till a user defined external surface (spherical or boundary of a volume) or is killed before if it reaches a user defined upper energy limit that represents the maximum energy of the external source. During the reverse tracking, reverse processes take place where the adjoint particle being tracked can be either scattered or transformed in another type of adjoint particle. During the reverse tracking the G4AdjointSimulationManager replaces the user defined primary, run, stepping, ... actions, by its own actions. A reverse tracking phase corresponds to one Geant4 event.

3.7.3.1.2. Forward tracking phase

When an adjoint particle reaches the external surface its weight, type, position, and direction are registered and a normal primary particle, with a type equivalent to the last generated primary adjoint, is generated with the same energy, position but opposite direction and is tracked in the forward direction in the sensitive region as in a forward MC simulation. During this forward tracking phase the event, stacking, stepping, tracking actions defined by the user for his forward simulation are used. By this clear separation between adjoint and forward tracking phases, the code of the user developed for a forward simulation should be only slightly modified to adapt it for an adjoint simulation (see Section 3.7.3.2). Indeed the computation of the signals is done by the same actions or classes that the one used in the forward simulation mode. A forward tracking phase corresponds to one G4 event.

3.7.3.1.3. Reverse processes

During the reverse tracking, reverse processes act on the adjoint particles. The reverse processes that are at the moment available in Geant4 are the:

- Reverse discrete ionization for e-, proton and ions
- Continuous gain of energy by ionization and bremsstrahlung for e- and by ionization for protons and ions
- Reverse discrete e- bremsstrahlung
- Reverse photo-electric effect
- Reverse Compton scattering
- Approximated multiple scattering (see comment in Section 3.7.3.4.3)

It is important to note that the electromagnetic reverse processes are cut dependent as their equivalent forward processes. The implementation of the reverse processes is based on the forward processes implemented in the G4 standard electromagnetic package.

3.7.3.1.4. Nb of adjoint particle types and nb of G4 events of an adjoint simulation

The list of type of adjoint and forward particles that are generated on the adjoint source and considered in the simulation is a function of the adjoint processes declared in the physics list. For example if only the e- and gamma electromagnetic processes are considered, only adjoint e- and adjoint gamma will be considered as primaries. In this case an adjoint event will be divided in four G4 event consisting in the reverse tracking of an adjoint e-, the forward tracking of its equivalent forward e-, the reverse tracking of an adjoint gamma, and the forward tracking of its equivalent forward gamma. In this case a run of 100 adjoint events will consist into 400 Geant4 events. If the proton ionization is also considered adjoint and forward protons are also generated as primaries and 600 Geant4 events are processed for 100 adjoint events.

3.7.3.2. How to update a G4 application to use the reverse Monte Carlo mode

Some modifications are needed to an existing Geant4 application in order to adapt it for the use of the reverse simulation mode (see also the G4 example **examples/extended/biasing/ReverseMC01**). It consists into the:

- Creation of the adjoint simulation manager in the main code
- Optional declaration of user actions that will be used during the adjoint tracking phase
- Use of a special physics lists that combine the adjoint and forward processes
- Modification of the user analysis part of the code

3.7.3.2.1. Creation of G4AdjointSimManager in the main

The class G4AdjointSimManager represents the manager of an adjoint simulation. This static class should be created somewhere in the main code. The way to do that is illustrated below

```
int main(int argc,char** argv) {
   ...
   G4AdjointSimManager* theAdjointSimManager = G4AdjointSimManager::GetInstance();
   ...
}
```

By doing this the G4 application can be run in the reverse MC mode as well as in the forward MC mode. It is important to note that G4AdjointSimManager is not a new G4RunManager and that the creation of G4RunManager in the main and the declaration of the geometry, physics list, and user actions to G4RunManager is still needed. The definition of the adjoint and external sources and the start of an adjoint simulation can be controlled by G4UI commands in the directory **/adjoint**.

3.7.3.2.2. Optional declaration of adjoint user actions

During an adjoint simulation the user stepping, tracking, stacking and event actions declared to G4RunManager are used only during the G4 events dedicated to the forward tracking of normal particles in the sensitive region, while during the events where adjoint particles are tracked backward the following happen concerning these actions:

- The user stepping action is replaced by G4AdjointSteppingAction that is reponsible to stop an adjoint track when it reaches the external source, exceed the maximum energy of the external source, or cross the adjoint source surface. If needed the user can declare its own stepping action that will be called by G4AdjointSteppingAction after the check of stopping track conditions. This stepping action can be different that the stepping action used for the forward simulation. It is declared to G4AdjointSimManager by the following lines of code :

  ```
  G4AdjointSimManager* theAdjointSimManager = G4AdjointSimManager::GetInstance();
  theAdjointSimManager->SetAdjointSteppingAction(aUserDefinedSteppingAction);
  ```
- No stacking, tracking and event actions are considered by default. If needed the user can declare to G4AdjointSimManager stacking, tracking and event actions that will be used only during the adjoint tracking phase. The following lines of code show how to declare these adjoint actions to G4AdjointSimManager:

  ```
  G4AdjointSimManager* theAdjointSimManager = G4AdjointSimManager::GetInstance();
  theAdjointSimManager->SetAdjointEventAction(aUserDefinedEventAction);
  theAdjointSimManager->SetAdjointStackingAction(aUserDefinedStackingAction);
  theAdjointSimManager->SetAdjointTrackingAction(aUserDefinedTrackingAction);
  ```

By default no user run action is considered in an adjoint simulation but if needed such action can be declared to G4AdjointSimManager as such:

```
G4AdjointSimManager* theAdjointSimManager = G4AdjointSimManager::GetInstance();
theAdjointSimManager->SetAdjointRunAction(aUserDefinedRunAction);
```

3.7.3.2.3. Physics list for reverse and forward electromagnetic processes

To run an adjoint simulation a specific physics list should be used where existing G4 adjoint electromagnetic processes and their forward equivalent have to be declared. An example of such physics list is provided by the class G4AdjointPhysicsLits in the G4 example **extended/biasing/ReverseMC01**.

3.7.3.2.4. Modification in the analysis part of the code

The user code should be modified to normalize the signals computed during the forward tracking phase to the weight of the last adjoint particle that reaches the external surface. This weight represents the statistical weight that the last full adjoint tracks (from the adjoint source to the external source) would have in a forward simulation. If multiplied by a signal and registered in function of energy and/or direction the simulation results will give an answer matrix of this signal. To normalize it to a given spectrum it has to be furthermore multiplied by a directional

differential flux corresponding to this spectrum The weight, direction, position , kinetic energy and type of the last adjoint particle that reaches the external source, and that would represents the primary of a forward simulation, can be get from G4AdjointSimManager by using for example the following line of codes

```
  G4AdjointSimManager* theAdjointSimManager = G4AdjointSimManager::GetInstance();
  G4String particle_name = theAdjointSimManager->GetFwdParticleNameAtEndOfLastAdjointTrack();
  G4int PDGEncoding= theAdjointSimManager->GetFwdParticlePDGEncodingAtEndOfLastAdjointTrack();
  G4double weight = theAdjointSimManager->GetWeightAtEndOfLastAdjointTrack();
  G4double Ekin  = theAdjointSimManager->GetEkinAtEndOfLastAdjointTrack();
  G4double Ekin_per_nuc=theAdjointSimManager->GetEkinNucAtEndOfLastAdjointTrack(); // in case of ions
  G4ThreeVector dir =  theAdjointSimManager->GetDirectionAtEndOfLastAdjointTrack();
  G4ThreeVector pos = theAdjointSimManager->GetPositionAtEndOfLastAdjointTrack();
```

In order to have a code working for both forward and adjoint simulation mode, the extra code needed in user actions or analysis manager for the adjoint simulation mode can be separated to the code needed only for the normal forward simulation by using the following public method of G4AdjointSimManager:

```
G4bool GetAdjointSimMode();
```

that returns true if an adjoint simulation is running and false if not.

The following code example shows how to normalize a detector signal and compute an answer matrix in the case of an adjoint simulation.

Example 3.5. Normalization in the case of an adjoint simulation. The detector signal S computed during the forward tracking phase is normalized to a primary source of e- with a differential directional flux given by the function F. An answer matrix of the signal is also computed.

```
  G4double S = ...; // signal   in the sensitive volume computed during a forward tracking phase

  //Normalization of the signal for an adjoint simulation
  G4AdjointSimManager* theAdjSimManager =    G4AdjointSimManager::GetInstance();
  if (theAdjSimManager->GetAdjointSimMode()) {
       G4double normalized_S=0.; //normalized to a given  e- primary spectrum
G4double S_for_answer_matrix=0.; //for e- answer matrix

if (theAdjSimManager->GetFwdParticleNameAtEndOfLastAdjointTrack() == "e-"){
    G4double ekin_prim = theAdjSimManager->GetEkinAtEndOfLastAdjointTrack();
    G4ThreeVector dir_prim =  theAdjointSimManager->GetDirectionAtEndOfLastAdjointTrack();
    G4double weight_prim = theAdjSimManager->GetWeightAtEndOfLastAdjointTrack();
    S_for_answer_matrix = S*weight_prim;
    normalized_S = S_for_answer_matrix*F(ekin_prim,dir); //F(ekin_prim,dir_prim) gives the differential directional
}
      //follows the code where normalized_S  and S_for_answer_matrix are  registered or whatever
       ....
  }

  //analysis/normalization code for forward simulation
  else {
    ...
  }
  ...
```

3.7.3.3. Control of an adjoint simulation

The G4UI commands in the directory /adjoint. allow the user to :

- Define the adjoint source where adjoint primaries are generated
- Define the external source till which adjoint particles are tracked
- Start an adjoint simulation

3.7.3.4. Known issues in the Reverse MC mode

3.7.3.4.1. Occasional wrong high weight in the adjoint simulation

In rare cases an adjoint track may get a wrong high weight when reaching the external source. While this happens not often it may corrupt the simulation results significantly. This happens in some tracks where both reverse photo-electric and bremsstrahlung processes take place at low energy. We still need some investigations to remove this problem at the level of physical adjoint/reverse processes. However this problem can be solved at the level of event actions or analysis in the user code by adding a test on the normalized signal during an adjoint simulation. An example of such test has been implemented in the Geant4 example **extended/biasing/ReverseMC01** . In this implementation an event is rejected when the relative error of the computed normalized energy deposited increases during one event by more than 50% while the computed precision is already below 10%.

3.7.3.4.2. Reverse bremsstrahlung

A difference between the differential cross sections used in the adjoint and forward bremsstrahlung models is the source of a higher flux of >100 keV gamma in the reverse simulation compared to the forward simulation mode. In principle the adjoint processes/models should make use of the direct differential cross section to sample the adjoint secondaries and compute the adjoint cross section. However due to the way the effective differential cross section is considered in the forward model G4eBremsstrahlungModel this was not possible to achieve for the reverse bremsstrahlung. Indeed the differential cross section used in G4AdjointeBremstrahlungModel is obtained by the numerical derivation over the cut energy of the direct cross section provided by G4eBremsstrahlungModel. This would be a correct procedure if the distribution of secondary in G4eBremsstrahlungModel would match this differential cross section. Unfortunately it is not the case as independent parameterization are used in G4eBremsstrahlungModel for both the cross sections and the sampling of secondaries. (It means that in the forward case if one would integrate the effective differential cross section considered in the simulation we would not find back the used cross section). In the future we plan to correct this problem by using an extra weight correction factor after the occurrence of a reverse bremsstrahlung. This weight factor should be the ratio between the differential CS used in the adjoint simulation and the one effectively used in the forward processes. As it is impossible to have a simple and direct access to the forward differential CS in G4eBremsstrahlungModel we are investigating the feasibility to use the differential CS considered in G4Penelope models.

3.7.3.4.3. Reverse multiple scattering

For the reverse multiple scattering the same model is used than in the forward case. This approximation makes that the discrepancy between the adjoint and forward simulation cases can get to a level of ~ 10-15% relative differences in the test cases that we have considered. In the future we plan to improve the adjoint multiple scattering models by forcing the computation of multiple scattering effect at the end of an adjoint step.

Chapter 4. Detector Definition and Response

4.1. Geometry

4.1.1. Introduction

The detector definition requires the representation of its geometrical elements, their materials and electronics properties, together with visualization attributes and user defined properties. The geometrical representation of detector elements focuses on the definition of solid models and their spatial position, as well as their logical relations to one another, such as in the case of containment.

Geant4 uses the concept of "Logical Volume" to manage the representation of detector element properties. The concept of "Physical Volume" is used to manage the representation of the spatial positioning of detector elements and their logical relations. The concept of "Solid" is used to manage the representation of the detector element solid modeling. Volumes and solids must be dynamically allocated in the user program; objects allocated are automatically registered in dedicated stores which also take care to free the memory at the end of a job.

The Geant4 solid modeler is STEP compliant. STEP is the ISO standard defining the protocol for exchanging geometrical data between CAD systems. This is achieved by standardizing the representation of solid models via the EXPRESS object definition language, which is part of the STEP ISO standard.

4.1.2. Solids

The STEP standard supports multiple solid representations. Constructive Solid Geometry (CSG) representations and Boundary Represented Solids (BREPs) are available. Different representations are suitable for different purposes, applications, required complexity, and levels of detail. CSG representations are easy to use and normally give superior performance, but they cannot reproduce complex solids such as those used in CAD systems. BREP representations can handle more extended topologies and reproduce the most complex solids.

All constructed solids can stream out their contents via appropriate methods and streaming operators.

For all solids it is possible to estimate the geometrical volume and the surface area by invoking the methods:

```
G4double GetCubicVolume()
G4double GetSurfaceArea()
```

which return an estimate of the solid volume and total area in internal units respectively. For elementary solids the functions compute the exact geometrical quantities, while for composite or complex solids an estimate is made using Monte Carlo techniques.

For all solids it is also possible to generate pseudo-random points lying on their surfaces, by invoking the method

```
G4ThreeVector GetPointOnSurface() const
```

which returns the generated point in local coordinates relative to the solid.

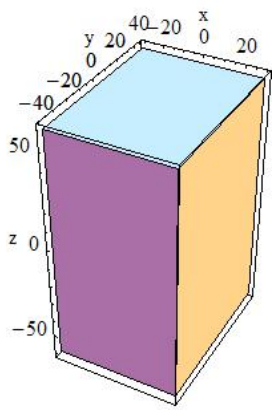
4.1.2.1. Constructed Solid Geometry (CSG) Solids

CSG solids are defined directly as three-dimensional primitives. They are described by a minimal set of parameters necessary to define the shape and size of the solid. CSG solids are Boxes, Tubes and their sections, Cones and their sections, Spheres, Wedges, and Toruses.

Box:

To create a **box** one can use the constructor:

```
G4Box(const G4String& pName,
            G4double  pX,
            G4double  pY,
            G4double  pZ)
```



In the picture:

`pX = 30, pY = 40, pZ = 60`

by giving the box a name and its half-lengths along the X, Y and Z axis:

`pX`	half length in X	`pY`	half length in Y	`pZ`	half length in Z

This will create a box that extends from `-pX` to `+pX` in X, from `-pY` to `+pY` in Y, and from `-pZ` to `+pZ` in Z.

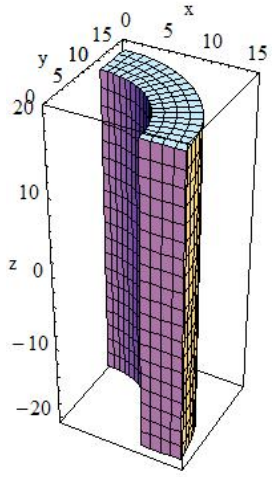
For example to create a box that is 2 by 6 by 10 centimeters in full length, and called `BoxA` one should use the following code:

```
G4Box* aBox = new G4Box("BoxA", 1.0*cm, 3.0*cm, 5.0*cm);
```

Cylindrical Section or Tube:

Similarly to create a **cylindrical section** or **tube**, one would use the constructor:

```
G4Tubs(const G4String& pName,
             G4double  pRMin,
             G4double  pRMax,
             G4double  pDz,
             G4double  pSPhi,
             G4double  pDPhi)
```



In the picture:

`pRMin = 10, pRMax = 15, pDz = 20`

giving its name `pName` and its parameters which are:

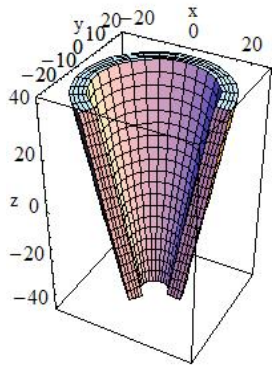
`pRMin`	Inner radius	`pRMax`	Outer radius

pDz	half length in z	pSPhi	the starting phi angle in radians
pDPhi	the angle of the segment in radians		

Cone or Conical section:

Similarly to create a **cone**, or **conical section**, one would use the constructor

```
G4Cons(const G4String& pName,
             G4double  pRmin1,
             G4double  pRmax1,
             G4double  pRmin2,
             G4double  pRmax2,
             G4double  pDz,
             G4double  pSPhi,
             G4double  pDPhi)
```



In the picture:

```
pRmin1 = 5, pRmax1 = 10, pRmin2
  = 20, pRmax2 = 25, pDz = 40,
    pSPhi = 0, pDPhi = 4/3*Pi
```

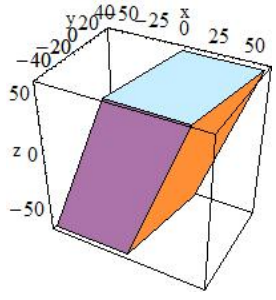
giving its name pName, and its parameters which are:

pRmin1	inside radius at -pDz	pRmax1	outside radius at -pDz
pRmin2	inside radius at +pDz	pRmax2	outside radius at +pDz
pDz	half length in z	pSPhi	starting angle of the segment in radians
pDPhi	the angle of the segment in radians		

Parallelepiped:

A **parallelepiped** is constructed using:

```
G4Para(const G4String& pName,
             G4double   dx,
             G4double   dy,
             G4double   dz,
             G4double   alpha,
             G4double   theta,
             G4double   phi)
```



In the picture:

```
dx = 30, dy = 40, dz = 60
```

giving its name pName and its parameters which are:

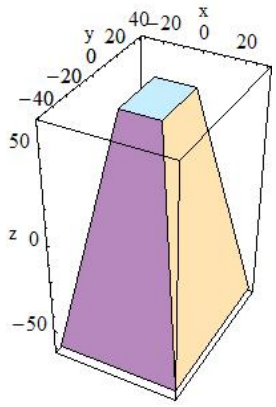
dx,dy,dz	Half-length in x,y,z

`alpha`	Angle formed by the y axis and by the plane joining the centre of the faces *parallel* to the z-x plane at -dy and +dy
`theta`	Polar angle of the line joining the centres of the faces at -dz and +dz in z
`phi`	Azimuthal angle of the line joining the centres of the faces at -dz and +dz in z

Trapezoid:

To construct a **trapezoid** use:

```
G4Trd(const G4String& pName,
            G4double  dx1,
            G4double  dx2,
            G4double  dy1,
            G4double  dy2,
            G4double  dz)
```



In the picture:

`dx1 = 30, dx2 = 10, dy1 = 40, dy2 = 15, dz = 60`

to obtain a solid with name `pName` and parameters

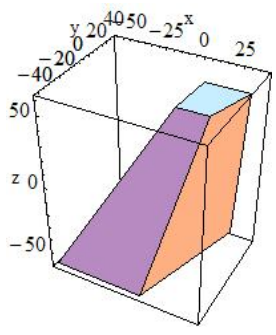
`dx1`	Half-length along x at the surface positioned at `-dz`
`dx2`	Half-length along x at the surface positioned at `+dz`
`dy1`	Half-length along y at the surface positioned at `-dz`
`dy2`	Half-length along y at the surface positioned at `+dz`
`dz`	Half-length along z axis

Generic Trapezoid:

To build a **generic trapezoid**, the `G4Trap` class is provided. Here are the two costructors for a Right Angular Wedge and for the general trapezoid for it:

```
G4Trap(const G4String& pName,
             G4double   pZ,
             G4double   pY,
             G4double   pX,
             G4double   pLTX)

G4Trap(const G4String& pName,
             G4double   pDz,   G4double   pTheta,
             G4double   pPhi,  G4double   pDy1,
             G4double   pDx1,  G4double   pDx2,
             G4double   pAlp1, G4double   pDy2,
             G4double   pDx3,  G4double   pDx4,
             G4double   pAlp2)
```



In the picture:

```
  pDx1 = 30, pDx2 = 40, pDy1 = 40,
  pDx3 = 10, pDx4 = 14, pDy2 = 16,
pDz = 60, pTheta = 20*Degree, pPhi =
 5*Degree, pAlp1 = pAlp2 = 10*Degree
```

to obtain a Right Angular Wedge with name `pName` and parameters:

`pZ`	Length along z
`pY`	Length along y
`pX`	Length along x at the wider side
`pLTX`	Length along x at the narrower side (`plTX<=pX`)

or to obtain the general trapezoid (see the Software Reference Manual):

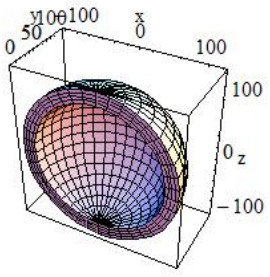
`pDx1`	Half x length of the side at y=-pDy1 of the face at -pDz
`pDx2`	Half x length of the side at y=+pDy1 of the face at -pDz
`pDz`	Half z length
`pTheta`	Polar angle of the line joining the centres of the faces at -/+pDz
`pPhi`	Azimuthal angle of the line joining the centre of the face at -pDz to the centre of the face at +pDz
`pDy1`	Half y length at -pDz
`pDy2`	Half y length at +pDz
`pDx3`	Half x length of the side at y=-pDy2 of the face at +pDz
`pDx4`	Half x length of the side at y=+pDy2 of the face at +pDz
`pAlp1`	Angle with respect to the y axis from the centre of the side (lower endcap)
`pAlp2`	Angle with respect to the y axis from the centre of the side (upper endcap)

Note on `pAlph1/2`: the two angles have to be the same due to the planarity condition.

Sphere or Spherical Shell Section:

To build a **sphere**, or a **spherical shell section**, use:

```
G4Sphere(const G4String& pName,
               G4double   pRmin,
               G4double   pRmax,
               G4double   pSPhi,
               G4double   pDPhi,
               G4double   pSTheta,
               G4double   pDTheta )
```



In the picture:

```
pRmin = 100, pRmax = 120,
pSPhi = 0*Degree, pDPhi =
180*Degree, pSTheta = 0 De-
gree, pDTheta = 180*Degree
```

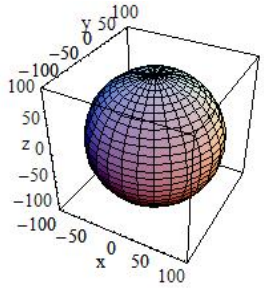
to obtain a solid with name `pName` and parameters:

pRmin	Inner radius
pRmax	Outer radius
pSPhi	Starting Phi angle of the segment in radians
pDPhi	Delta Phi angle of the segment in radians
pSTheta	Starting Theta angle of the segment in radians
pDTheta	Delta Theta angle of the segment in radians

Full Solid Sphere:

To build a **full solid sphere** use:

```
G4Orb(const G4String& pName,
            G4double  pRmax)
```



In the picture:

`pRmax = 100`

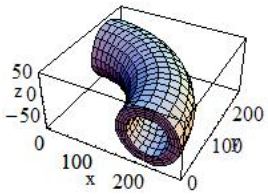
The Orb can be obtained from a Sphere with: `pRmin` = 0, `pSPhi` = 0, `pDPhi` = 2*Pi, `pSTheta` = 0, `pDTheta` = Pi

pRmax	Outer radius

Torus:

To build a **torus** use:

```
G4Torus(const G4String& pName,
              G4double   pRmin,
              G4double   pRmax,
              G4double   pRtor,
              G4double   pSPhi,
              G4double   pDPhi)
```



In the picture:

`pRmin = 40, pRmax = 60, pRtor = 200, pSPhi = 0, pDPhi = 90*Degree`

to obtain a solid with name `pName` and parameters:

pRmin	Inside radius
pRmax	Outside radius
pRtor	Swept radius of torus
pSPhi	Starting Phi angle in radians (`fSPhi+fDPhi<=2PI`, `fSPhi>-2PI`)
pDPhi	Delta angle of the segment in radians

In addition, the Geant4 Design Documentation shows in the Solids Class Diagram the complete list of CSG classes, and the STEP documentation contains a detailed EXPRESS description of each CSG solid.

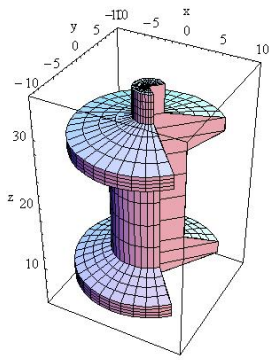
Specific CSG Solids

Polycons:

Polycons (PCON) are implemented in Geant4 through the `G4Polycon` class:

```
G4Polycone(const G4String& pName,
                 G4double   phiStart,
                 G4double   phiTotal,
                 G4int      numZPlanes,
                 const G4double   zPlane[],
                 const G4double   rInner[],
                 const G4double   rOuter[])

G4Polycone(const G4String& pName,
                 G4double   phiStart,
                 G4double   phiTotal,
                 G4int      numRZ,
                 const G4double  r[],
                 const G4double  z[])
```



In the picture:

```
phiStart = 1/4*Pi, phiTotal =
 3/2*Pi, numZPlanes = 9, rIn-
ner = { 0, 0, 0, 0, 0, 0, 0, 0,
 0}, rOuter = { 0, 10, 10, 5 ,
 5, 10 , 10 , 2, 2}, z = { 5,
7, 9, 11, 25, 27, 29, 31, 35 }
```

where:

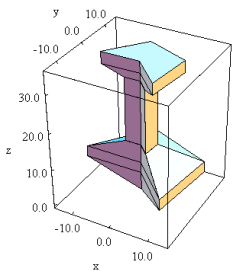
phiStart	Initial Phi starting angle
phiTotal	Total Phi angle
numZPlanes	Number of z planes
numRZ	Number of corners in r,z space
zPlane	Position of z planes
rInner	Tangent distance to inner surface
rOuter	Tangent distance to outer surface
r	r coordinate of corners
z	z coordinate of corners

Polyhedra (PGON):

Polyhedra (PGON) are implemented through `G4Polyhedra`:

```
G4Polyhedra(const G4String& pName,
                  G4double  phiStart,
                  G4double  phiTotal,
                  G4int     numSide,
                  G4int     numZPlanes,
            const G4double  zPlane[],
            const G4double  rInner[],
            const G4double  rOuter[] )

G4Polyhedra(const G4String& pName,
                  G4double  phiStart,
```



```
                    G4double  phiTotal,
                    G4int     numSide,
                    G4int     numRZ,
              const G4double  r[],
              const G4double  z[] )
```

In the picture:

```
phiStart = -1/4*Pi, phiTo-
tal= 5/4*Pi, numSide = 3, nun-
ZPlanes = 7, rInner = { 0, 0,
0, 0, 0, 0, 0 }, rOuter = { 0,
15, 15, 4, 4, 10, 10 }, z =
{ 0, 5, 8, 13 , 30, 32, 35 }
```

where:

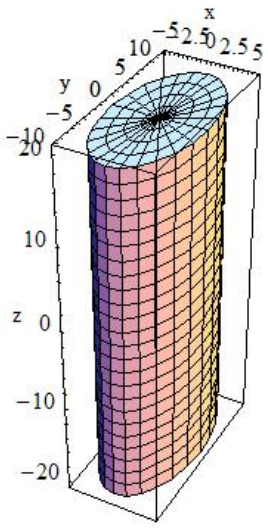
`phiStart`	Initial Phi starting angle
`phiTotal`	Total Phi angle
`numSide`	Number of sides
`numZPlanes`	Number of z planes
`numRZ`	Number of corners in r,z space
zPlane	Position of z planes
`rInner`	Tangent distance to inner surface
rOuter	Tangent distance to outer surface
`r`	r coordinate of corners
`z`	z coordinate of corners

Tube with an elliptical cross section:

A **tube with an elliptical cross section** (ELTU) can be defined as follows:

```
G4EllipticalTube(const G4String& pName,
                       G4double  Dx,
                       G4double  Dy,
                       G4double  Dz)
```

The equation of the surface in x/y is `1.0 = (x/dx)**2 +(y/dy)**2`



In the picture:

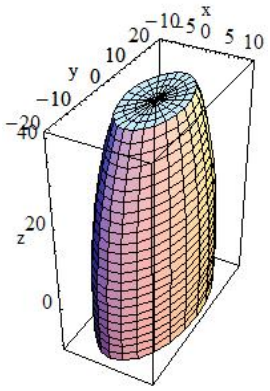
`Dx = 5, Dy = 10, Dz = 20`

Dx	Half length X	Dy	Half length Y	Dz	Half length Z

General Ellipsoid:

The general **ellipsoid** with possible cut in `Z` can be defined as follows:

```
G4Ellipsoid(const G4String& pName,
                  G4double  pxSemiAxis,
                  G4double  pySemiAxis,
                  G4double  pzSemiAxis,
                  G4double  pzBottomCut=0,
                  G4double  pzTopCut=0)
```



In the picture:

`pxSemiAxis = 10, pySemiAxis = 20, pzSemiAxis = 50, pzBottomCut = -10, pzTopCut = 40`

A general (or triaxial) ellipsoid is a quadratic surface which is given in Cartesian coordinates by:

```
1.0 = (x/pxSemiAxis)**2 + (y/pySemiAxis)**2 + (z/pzSemiAxis)**2
```

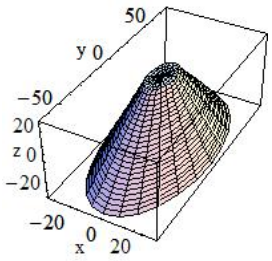
where:

`pxSemiAxis`	Semiaxis in X
pySemiAxis	Semiaxis in Y
pzSemiAxis	Semiaxis in Z
pzBottomCut	lower cut plane level, z
pzTopCut	upper cut plane level, z

Cone with Elliptical Cross Section:

A **cone with an elliptical cross section** can be defined as follows:

```
G4EllipticalCone(const G4String& pName,
                       G4double  pxSemiAxis,
                       G4double  pySemiAxis,
                       G4double  zMax,
                       G4double  pzTopCut)
```



In the picture:

`pxSemiAxis = 30/75, pySemiAxis = 60/75, zMax = 50, pzTopCut = 25`

where:

pxSemiAxis	Semiaxis in X
pySemiAxis	Semiaxis in Y
zMax	Height of elliptical cone
pzTopCut	upper cut plane level

An elliptical cone of height `zMax`, semiaxis `pxSemiAxis`, and semiaxis `pySemiAxis` is given by the parametric equations:

```
x = pxSemiAxis * ( zMax - u ) / u * Cos(v)
y = pySemiAxis * ( zMax - u ) / u * Sin(v)
z = u
```

Where `v` is between `0` and `2*Pi`, and `u` between `0` and `h` respectively.

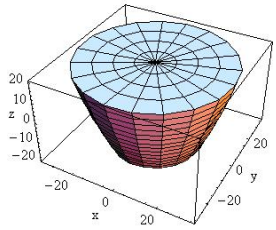
Paraboloid, a solid with parabolic profile:

A **solid with parabolic profile** and possible cuts along the `Z` axis can be defined as follows:

```
G4Paraboloid(const G4String& pName,
                   G4double  Dz,
                   G4double  R1,
                   G4double  R2)
```

The equation for the solid is:

```
rho**2 <= k1 * z + k2;
    -dz <= z <= dz
r1**2 = k1 * (-dz) + k2
r2**2 = k1 * ( dz) + k2
```



In the picture:

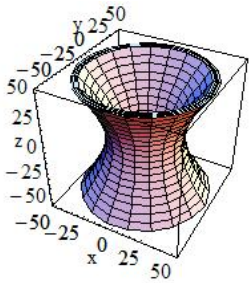
`R1 = 20, R2 = 35, Dz = 20`

Dz	Half length Z	R1	Radius at -Dz	R2	Radius at +Dz greater than R1

Tube with Hyperbolic Profile:

A **tube with a hyperbolic profile** (HYPE) can be defined as follows:

```
G4Hype(const G4String& pName,
             G4double  innerRadius,
             G4double  outerRadius,
             G4double  innerStereo,
             G4double  outerStereo,
             G4double  halfLenZ)
```



In the picture:

`innerStereo = 0.7, outerStereo = 0.7, halfLenZ = 50, innerRadius = 20, outerRadius = 30`

`G4Hype` is shaped with curved sides parallel to the `z`-axis, has a specified half-length along the `z` axis about which it is centred, and a given minimum and maximum radius.

A minimum radius of `0` defines a filled Hype (with hyperbolic inner surface), i.e. inner radius = 0 AND inner stereo angle = 0.

The inner and outer hyperbolic surfaces can have different stereo angles. A stereo angle of `0` gives a cylindrical surface:

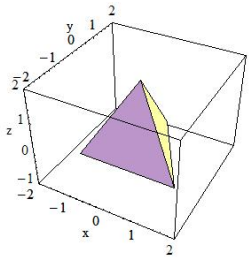
`innerRadius`	Inner radius
`outerRadius`	Outer radius
`innerStereo`	Inner stereo angle in radians
`outerStereo`	Outer stereo angle in radians

halfLenZ	Half length in Z

Tetrahedra:

A **tetrahedra** solid can be defined as follows:

```
G4Tet(const G4String& pName,
            G4ThreeVector  anchor,
            G4ThreeVector  p2,
            G4ThreeVector  p3,
            G4ThreeVector  p4,
            G4bool         *degeneracyFlag=0)
```



In the picture:

```
anchor = {0, 0, sqrt(3)},
p2 = { 0, 2*sqrt(2/3), -1/
sqrt(3) }, p3 = { -sqrt(2), -
sqrt(2/3),-1/sqrt(3) }, p4 =
{ sqrt(2), -sqrt(2/3) , -1/sqrt(3) }
```

The solid is defined by 4 points in space:

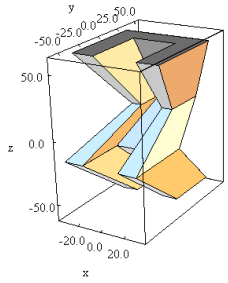
anchor	Anchor point
p2	Point 2
p3	Point 3
p4	Point 4
degeneracyFlag	Flag indicating degeneracy of points

Extruded Polygon:

The extrusion of an arbitrary polygon (**extruded solid**) with fixed outline in the defined Z sections can be defined as follows (in a general way, or as special construct with two Z sections):

```
G4ExtrudedSolid(const G4String&                pName,
                std::vector<G4TwoVector> polygon,
                std::vector<ZSection>    zsections)

G4ExtrudedSolid(const G4String&                pName,
                std::vector<G4TwoVector> polygon,
                G4double                 hz,
                G4TwoVector off1, G4double scale1,
                G4TwoVector off2, G4double scale2)
```



In the picture:

```
poligon = {-30,-30},{-30,30},
{30,30},{30,-30}, {15,-30},
{15,15},{-15,15},{-15,-30}

zsections = [-60,{0,30},0.8],
[-15, {0,-30},1.], [10,
{0,0},0.6], [60,{0,30},1.2]
```

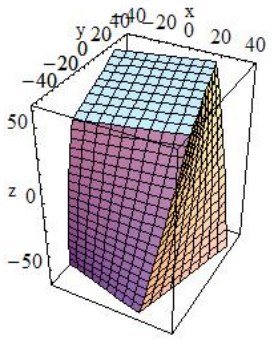
The z-sides of the solid are the scaled versions of the same polygon.

polygon	the vertices of the outlined polygon defined in clockwise order
zsections	the z-sections defined by z position in increasing order
hz	Half length in Z
off1, off2	Offset of the side in -hz and +hz respectively
scale1, scale2	Scale of the side in -hz and +hz respectively

Box Twisted:

A **box twisted** along one axis can be defined as follows:

```
G4TwistedBox(const G4String& pName,
                   G4double  twistedangle,
                   G4double  pDx,
                   G4double  pDy,
                   G4double  pDz)
```



In the picture:

```
twistedangle = 30*Degree,
pDx = 30, pDy =40, pDz = 60
```

G4TwistedBox is a box twisted along the z-axis. The twist angle cannot be greater than 90 degrees:

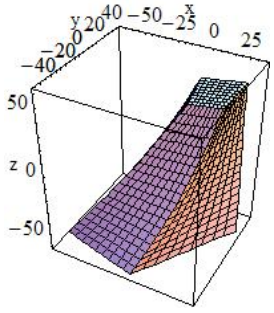
twistedangle	Twist angle
pDx	Half x length
pDy	Half y length
pDz	Half z length

Trapezoid Twisted along One Axis:

trapezoid twisted along one axis can be defined as follows:

```
G4TwistedTrap(const G4String& pName,
                    G4double  twistedangle,
                    G4double  pDxx1,
                    G4double  pDxx2,
                    G4double  pDy,
                    G4double   pDz)

G4TwistedTrap(const G4String& pName,
                    G4double  twistedangle,
                    G4double  pDz,
                    G4double  pTheta,
                    G4double  pPhi,
                    G4double  pDy1,
                    G4double  pDx1,
                    G4double  pDx2,
                    G4double  pDy2,
                    G4double  pDx3,
                    G4double  pDx4,
                    G4double  pAlph)
```



In the picture:

```
pDx1 = 30, pDx2 = 40, pDy1 = 40,
pDx3 = 10, pDx4 = 14, pDy2 = 16,
  pDz = 60, pTheta = 20*Degree,
pDphi = 5*Degree, pAlph = 10*De-
 gree, twistedangle = 30*Degree
```

The first constructor of `G4TwistedTrap` produces a regular trapezoid twisted along the `z`-axis, where the caps of the trapezoid are of the same shape and size.

The second constructor produces a generic trapezoid with polar, azimuthal and tilt angles.

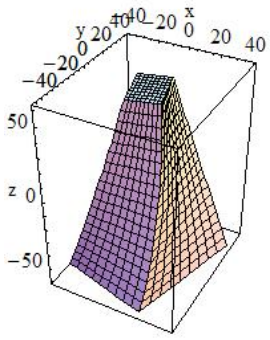
The twist angle cannot be greater than 90 degrees:

`twistedangle`	Twisted angle
`pDx1`	Half x length at y=-pDy
`pDx2`	Half x length at y=+pDy
`pDy`	Half y length
`pDz`	Half z length
`pTheta`	Polar angle of the line joining the centres of the faces at -/+pDz
`pDy1`	Half y length at -pDz
`pDx1`	Half x length at -pDz, y=-pDy1
`pDx2`	Half x length at -pDz, y=+pDy1
`pDy2`	Half y length at +pDz
`pDx3`	Half x length at +pDz, y=-pDy2
`pDx4`	Half x length at +pDz, y=+pDy2
`pAlph`	Angle with respect to the y axis from the centre of the side

Twisted Trapezoid with x and y dimensions varying along z:

A **twisted trapezoid** with the `x` and `y` dimensions **varying along `z`** can be defined as follows:

```
G4TwistedTrd(const G4String& pName,
                   G4double  pDx1,
                   G4double  pDx2,
                   G4double  pDy1,
                   G4double  pDy2,
                   G4double  pDz,
                   G4double  twistedangle)
```



In the picture:

```
dx1 = 30, dx2 = 10, dy1
= 40, dy2 = 15, dz = 60,
twistedangle = 30*Degree
```

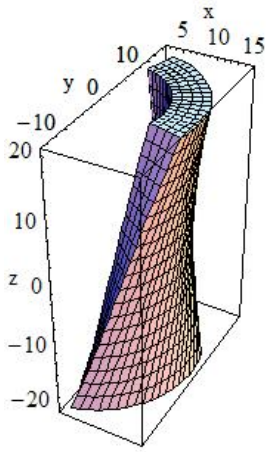
where:

`pDx1`	Half x length at the surface positioned at -dz
`pDx2`	Half x length at the surface positioned at +dz
`pDy1`	Half y length at the surface positioned at -dz
`pDy2`	Half y length at the surface positioned at +dz
`pDz`	Half z length
`twistedangle`	Twisted angle

Tube Section Twisted along Its Axis:

A **tube section twisted** along its axis can be defined as follows:

```
G4TwistedTubs(const G4String& pName,
                    G4double  twistedangle,
                    G4double  endinnerrad,
                    G4double  endouterrad,
                    G4double  halfzlen,
                    G4double  dphi)
```



In the picture:

`endinnerrad = 10, endouterrad = 15, halfzlen = 20, dphi = 90*Degree, twistedangle = 60*Degree`

`G4TwistedTubs` is a sort of twisted cylinder which, placed along the `z`-axis and divided into `phi`-segments is shaped like an hyperboloid, where each of its segmented pieces can be tilted with a stereo angle.

It can have inner and outer surfaces with the same stereo angle:

`twistedangle`	Twisted angle
`endinnerrad`	Inner radius at endcap
`endouterrad`	Outer radius at endcap
`halfzlen`	Half z length
`dphi`	Phi angle of a segment

Additional constructors are provided, allowing the shape to be specified either as:

- the number of segments in `phi` and the total angle for all segments, or
- a combination of the above constructors providing instead the inner and outer radii at `z=0` with different `z`-lengths along negative and positive `z`-axis.

4.1.2.2. Solids made by Boolean operations

Simple solids can be combined using Boolean operations. For example, a cylinder and a half-sphere can be combined with the union Boolean operation.

Creating such a new *Boolean* solid, requires:

- Two solids
- A Boolean operation: union, intersection or subtraction.
- Optionally a transformation for the second solid.

The solids used should be either CSG solids (for examples a box, a spherical shell, or a tube) or another Boolean solid: the product of a previous Boolean operation. An important purpose of Boolean solids is to allow the description of solids with peculiar shapes in a simple and intuitive way, still allowing an efficient geometrical navigation inside them.

The solids used can actually be of any type. However, in order to fully support the export of a Geant4 solid model via STEP to CAD systems, we restrict the use of Boolean operations to this subset of solids. But this subset contains all the most interesting use cases.

The constituent solids of a Boolean operation should possibly *avoid* be composed by sharing all or part of their surfaces. This precaution is necessary in order to avoid the generation of 'fake' surfaces due to precision loss, or errors in the final visualization of the Boolean shape. Moreover, the final Boolean solid should represent a single 'closed' solid, i.e. a Boolean operation between two solids which are disjoint or far apart each other, is *not* a valid Boolean composition.

The tracking cost for navigating in a Boolean solid in the current implementation, is proportional to the number of constituent solids. So care must be taken to avoid extensive, unecessary use of Boolean solids in performance-critical areas of a geometry description, where each solid is created from Boolean combinations of many other solids.

Examples of the creation of the simplest Boolean solids are given below:

```
G4Box*  box =
  new G4Box("Box",20*mm,30*mm,40*mm);
G4Tubs* cyl =
  new G4Tubs("Cylinder",0,50*mm,50*mm,0,twopi);  // r:     0 mm -> 50 mm
                                                 // z:   -50 mm -> 50 mm
                                                 // phi:   0 ->  2 pi
G4UnionSolid* union =
  new G4UnionSolid("Box+Cylinder", box, cyl);
G4IntersectionSolid* intersection =
  new G4IntersectionSolid("Box*Cylinder", box, cyl);
G4SubtractionSolid* subtraction =
  new G4SubtractionSolid("Box-Cylinder", box, cyl);
```

where the union, intersection and subtraction of a box and cylinder are constructed.

The more useful case where one of the solids is displaced from the origin of coordinates also exists. In this case the second solid is positioned relative to the coordinate system (and thus relative to the first). This can be done in two ways:

- Either by giving a rotation matrix and translation vector that are used to transform the coordinate system of the second solid to the coordinate system of the first solid. This is called the *passive* method.
- Or by creating a transformation that moves the second solid from its desired position to its standard position, e.g., a box's standard position is with its centre at the origin and sides parallel to the three axes. This is called the *active* method.

In the first case, the translation is applied first to move the origin of coordinates. Then the rotation is used to rotate the coordinate system of the second solid to the coordinate system of the first.

```
  G4RotationMatrix* yRot = new G4RotationMatrix;  // Rotates X and Z axes only
  yRot->rotateY(M_PI/4.*rad);                     // Rotates 45 degrees
  G4ThreeVector zTrans(0, 0, 50);

  G4UnionSolid* unionMoved =
    new G4UnionSolid("Box+CylinderMoved", box, cyl, yRot, zTrans);
  //
  // The new coordinate system of the cylinder is translated so that
  // its centre is at +50 on the original Z axis, and it is rotated
  // with its X axis halfway between the original X and Z axes.

  // Now we build the same solid using the alternative method
  //
  G4RotationMatrix invRot = *(yRot->invert());
  G4Transform3D transform(invRot, zTrans);
  G4UnionSolid* unionMoved =
    new G4UnionSolid("Box+CylinderMoved", box, cyl, transform);
```

Note that the first constructor that takes a pointer to the rotation-matrix (`G4RotationMatrix*`), does NOT copy it. Therefore once used a rotation-matrix to construct a Boolean solid, it must NOT be modified.

In contrast, with the alternative method shown, a `G4Transform3D` is provided to the constructor by value, and its transformation is stored by the Boolean solid. The user may modify the `G4Transform3D` and eventually use it again.

When positioning a volume associated to a Boolean solid, the relative center of coordinates considered for the positioning is the one related to the *first* of the two constituent solids.

4.1.2.3. Boundary Represented (BREPS) Solids

BREP solids are defined via the description of their boundaries. The boundaries can be made of planar and second order surfaces. Eventually these can be trimmed and have holes. The resulting solids, such as polygonal, polyconical solids are known as Elementary BREPS.

In addition, the boundary surfaces can be made of Bezier surfaces and B-Splines, or of NURBS (Non-Uniform-Rational-B-Splines) surfaces. The resulting solids are Advanced BREPS.

> Currently, the implementation for surfaces generated by Beziers, B-Splines or NURBS is only at the level of prototype and not fully functional.
>
> Extensions in this area are foreseen in future.

A few elementary BREPS are provided in the BREPS module as examples on how to assemble a BREP shap; these can be instantiated in the same manner as for the Constructed Solids (CSGs). We summarize their capabilities in the following section.

Most BREPS Solids are however defined by creating each surface separately and tying them together.

Specific BREP Solids:

We have defined one polygonal and one polyconical shape using BREPS. The polycone provides a shape defined by a series of conical sections with the same axis, contiguous along it.

The polyconical solid `G4BREPSolidPCone` is a shape defined by a set of inner and outer conical or cylindrical surface sections and two planes perpendicular to the Z axis. Each conical surface is defined by its radius at two different planes perpendicular to the Z-axis. Inner and outer conical surfaces are defined using common Z planes.

```
G4BREPSolidPCone( const G4String& pName,
                        G4double  start_angle,
                        G4double  opening_angle,
                        G4int     num_z_planes,    // sections,
                        G4double  z_start,
                  const G4double  z_values[],
                  const G4double  RMIN[],
                  const G4double  RMAX[]  )
```

The conical sections do not need to fill 360 degrees, but can have a common start and opening angle.

`start_angle`	starting angle
`opening_angle`	opening angle
`num_z_planes`	number of planes perpendicular to the z-axis used.
`z_start`	starting value of z
`z_values`	z coordinates of each plane
`RMIN`	radius of inner cone at each plane
`RMAX`	radius of outer cone at each plane

The polygonal solid `G4BREPSolidPolyhedra` is a shape defined by an inner and outer polygonal surface and two planes perpendicular to the Z axis. Each polygonal surface is created by linking a series of polygons created

at different planes perpendicular to the Z-axis. All these polygons all have the same number of sides (`sides`) and are defined at the same Z planes for both inner and outer polygonal surfaces.

The polygons do not need to fill 360 degrees, but have a start and opening angle.

The constructor takes the following parameters:

```
G4BREPSolidPolyhedra( const G4String& pName,
                            G4double  start_angle,
                            G4double  opening_angle,
                            G4int     sides,
                            G4int     num_z_planes,
                            G4double  z_start,
                      const G4double  z_values[],
                      const G4double  RMIN[],
                      const G4double  RMAX[]  )
```

which in addition to its name have the following meaning:

`start_angle`	starting angle
`opening_angle`	opening angle
`sides`	number of sides of each polygon in the x-y plane
`num_z_planes`	number of planes perpendicular to the z-axis used.
`z_start`	starting value of z
`z_values`	z coordinates of each plane
`RMIN`	radius of inner polygon at each corner
`RMAX`	radius of outer polygon at each corner

the shape is defined by the number of sides `sides` of the polygon in the plane perpendicular to the z-axis.

4.1.2.4. Tessellated Solids

In Geant4 it is also implemented a class `G4TessellatedSolid` which can be used to generate a generic solid defined by a number of facets (`G4VFacet`). Such constructs are especially important for conversion of complex geometrical shapes imported from CAD systems bounded with generic surfaces into an approximate description with facets of defined dimension (see Figure 4.1).

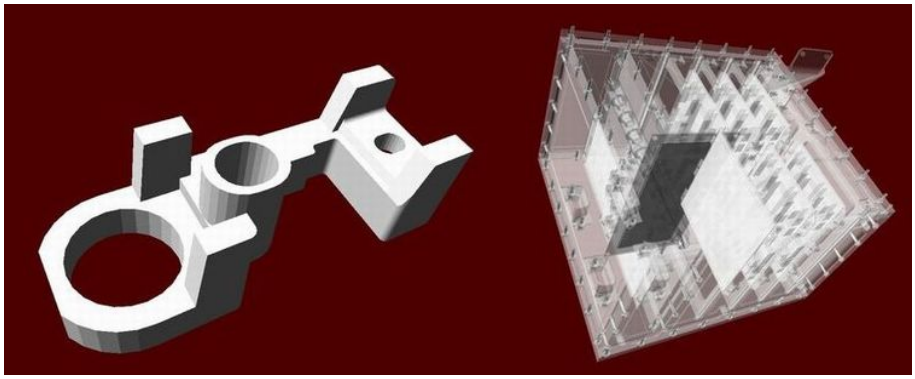


Figure 4.1. Example of geometries imported from CAD system and converted to tessellated solids.

They can also be used to generate a solid bounded with a generic surface made of planar facets. It is important that the supplied facets shall form a fully enclose space to represent the solid.

Two types of facet can be used for the construction of a `G4TessellatedSolid`: a triangular facet (`G4TriangularFacet`) and a quadrangular facet (`G4QuadrangularFacet`).

An example on how to generate a simple tessellated shape is given below.

Example 4.1. An example of a simple tessellated solid with `G4TessellatedSolid`.

```
// First declare a tessellated solid
//
G4TessellatedSolid solidTarget = new G4TessellatedSolid("Solid_name");

// Define the facets which form the solid
//
G4double targetSize = 10*cm ;
G4TriangularFacet *facet1 = new
G4TriangularFacet (G4ThreeVector(-targetSize,-targetSize,        0.0),
                   G4ThreeVector(+targetSize,-targetSize,        0.0),
                   G4ThreeVector(        0.0,        0.0,+targetSize),
                   ABSOLUTE);
G4TriangularFacet *facet2 = new
G4TriangularFacet (G4ThreeVector(+targetSize,-targetSize,        0.0),
                   G4ThreeVector(+targetSize,+targetSize,        0.0),
                   G4ThreeVector(        0.0,        0.0,+targetSize),
                   ABSOLUTE);
G4TriangularFacet *facet3 = new
G4TriangularFacet (G4ThreeVector(+targetSize,+targetSize,        0.0),
                   G4ThreeVector(-targetSize,+targetSize,        0.0),
                   G4ThreeVector(        0.0,        0.0,+targetSize),
                   ABSOLUTE);
G4TriangularFacet *facet4 = new
G4TriangularFacet (G4ThreeVector(-targetSize,+targetSize,        0.0),
                   G4ThreeVector(-targetSize,-targetSize,        0.0),
                   G4ThreeVector(        0.0,        0.0,+targetSize),
                   ABSOLUTE);
G4QuadrangularFacet *facet5 = new
G4QuadrangularFacet (G4ThreeVector(-targetSize,-targetSize,        0.0),
                     G4ThreeVector(-targetSize,+targetSize,        0.0),
                     G4ThreeVector(+targetSize,+targetSize,        0.0),
                     G4ThreeVector(+targetSize,-targetSize,        0.0),
                     ABSOLUTE);

// Now add the facets to the solid
//
solidTarget->AddFacet((G4VFacet*) facet1);
solidTarget->AddFacet((G4VFacet*) facet2);
solidTarget->AddFacet((G4VFacet*) facet3);
solidTarget->AddFacet((G4VFacet*) facet4);
solidTarget->AddFacet((G4VFacet*) facet5);

Finally declare the solid is complete
//
solidTarget->SetSolidClosed(true);
```

The `G4TriangularFacet` class is used for the contruction of `G4TessellatedSolid`. It is defined by three vertices, which shall be supplied in *anti-clockwise order* looking from the outside of the solid where it belongs. Its constructor looks like:

```
G4TriangularFacet ( const G4ThreeVector     Pt0,
                    const G4ThreeVector     vt1,
                    const G4ThreeVector     vt2,
                          G4FacetVertexType fType )
```

i.e., it takes 4 parameters to define the three vertices:

`G4FacetVertexType`	`ABSOLUTE` in which case `Pt0`, `vt1` and `vt2` are the three vertices in anti-clockwise order looking from the outside.
`G4FacetVertexType`	`RELATIVE` in which case the first vertex is `Pt0`, the second vertex is `Pt0+vt1` and the third vertex is `Pt0+vt2`, all in anti-clockwise order when looking from the outside.

The `G4QuadrangularFacet` class can be used for the contruction of `G4TessellatedSolid` as well. It is defined by four vertices, which shall be in the same plane and be supplied in *anti-clockwise order* looking from the outside of the solid where it belongs. Its constructor looks like:

```
      G4QuadrangularFacet ( const G4ThreeVector     Pt0,
                            const G4ThreeVector     vt1,
                            const G4ThreeVector     vt2,
                            const G4ThreeVector     vt3,
                                  G4FacetVertexType fType )
```

i.e., it takes 5 parameters to define the four vertices:

`G4FacetVertexType`	`ABSOLUTE` in which case `Pt0`, `vt1`, `vt2` and `vt3` are the four vertices required in anti-clockwise order when looking from the outside.
`G4FacetVertexType`	`RELATIVE` in which case the first vertex is `Pt0`, the second vertex is `Pt0+vt`, the third vertex is `Pt0+vt2` and the fourth vertex is `Pt0+vt3`, in anti-clockwise order when looking from the outside.

Importing CAD models as tessellated shapes

Tessellated solids can also be used to import geometrical models from CAD systems (see Figure 4.1). In order to do this, it is required to convert first the CAD shapes into tessellated surfaces. A way to do this is to save the shapes in the geometrical model as STEP files and convert them to tessellated (faceted surfaces) solids, using a tool which allows such conversion. At the time of writing, at least two tools are available for such purpose: STViewer (part of the STEP-Tools development suite) or FASTRAD. This strategy allows to import any shape with some degree of approximation; the converted CAD models can then be imported through GDML (Geometry Description Markup Language) into Geant4 and be represented as `G4TessellatedSolid` shapes.

4.1.3. Logical Volumes

The Logical Volume manages the information associated with detector elements represented by a given Solid and Material, independently from its physical position in the detector.

A Logical Volume knows which physical volumes are contained within it. It is uniquely defined to be their mother volume. A Logical Volume thus represents a hierarchy of unpositioned volumes whose positions relative to one another are well defined. By creating Physical Volumes, which are placed instances of a Logical Volume, this hierarchy or tree can be repeated.

A Logical Volume also manages the information relative to the Visualization attributes (Section 8.6) and user-defined parameters related to tracking, electro-magnetic field or cuts (through the `G4UserLimits` interface).

By default, tracking optimization of the geometry (voxelization) is applied to the volume hierarchy identified by a logical volume. It is possible to change the default behavior by choosing not to apply geometry optimization for a given logical volume. This feature does not apply to the case where the associated physical volume is a parameterised volume; in this case, optimization is always applied.

```
   G4LogicalVolume( G4VSolid*             pSolid,
                    G4Material*           pMaterial,
                    const G4String&       Name,
                    G4FieldManager*       pFieldMgr=0,
                    G4VSensitiveDetector* pSDetector=0,
                    G4UserLimits*         pULimits=0,
                    G4bool                Optimise=true )
```

Through the logical volume it is also possible to *tune* the granularity of the optimisation algorithm to be applied to the sub-tree of volumes represented. This is possible using the methods:

```
   G4double GetSmartless() const
   void SetSmartless(G4double s)
```

The default *smartless* value is *2* and controls the average number of slices per contained volume which are used in the optimisation. The smaller the value, the less fine grained optimisation grid is generated; this will translate in a possible reduction of memory consumed for the optimisation of that portion of geometry at the price of a slight CPU time increase at tracking time. Manual tuning of the optimisation is in general not required, since the

optimal granularity level is computed automatically and adapted to the specific geometry setup; however, in some cases (like geometry portions with 'dense' concentration of volumes distributed in a non-uniform way), it may be necessary to adopt manual tuning for helping the optimisation process in dealing with the most critical areas. By setting the verbosity to *2* through the following UI run-time command:

```
/run/verbose 2
```

a statistics of the memory consumed for the allocated optimisation nodes will be displayed volume by volume, allowing to easily identify the critical areas which may eventually require manual intervention.

The logical volume provides a way to estimate the *mass* of a tree of volumes defining a detector or sub-detector. This can be achieved by calling the method:

```
G4double GetMass(G4bool forced=false)
```

The mass of the logical volume tree is computed from the estimated geometrical volume of each solid and material associated with the logical volume and its daughters. Note that this computation may require a considerable amount of time, depending on the complexity of the geometry tree. The returned value is cached by default and can be used for successive calls, unless recomputation is forced by providing `true` for the boolean argument `forced` in input. Computation should be forced if the geometry setup has changed after the previous call.

Finally, the Logical Volume manages the information relative to the Envelopes hierarchy required for fast Monte Carlo parameterisations (Section 5.2.6).

4.1.3.1. Sub-detector Regions

In complex geometry setups, such as those found in large detectors in particle physics experiments, it is useful to think of specific Logical Volumes as representing parts (sub-detectors) of the entire detector setup which perform specific functions. In such setups, the processing speed of a real simulation can be increased by assigning specific production *cuts* to each of these detector parts. This allows a more detailed simulation to occur only in those regions where it is required.

The concept of detector *Region* is introduced to address this need. Once the final geometry setup of the detector has been defined, a region can be specified by constructing it with:

```
G4Region( const G4String& rName )
```

where:

`rName`	String identifier for the detector region

A `G4Region` must then be assigned to a logical volume, in order to make it a *Root Logical Volume*:

```
G4Region* emCalorimeter = new G4Region("EM-Calorimeter");
emCalorimeter->AddRootLogicalVolume(emCalorimeter);
```

A root logical volume is the first volume at the top of the hierarchy to which a given region is assigned. Once the region is assigned to the root logical volume, the information is automatically propagated to the volume tree, so that each daughter volume shares the same region. Propagation on a tree branch will be interrupted if an already existing root logical volume is encountered.

A specific *Production Cut* can be assigned to the region, by defining and assigning to it a `G4ProductionCut` object

```
emCalorimeter->SetProductionCuts(emCalCuts);
```

Section 5.4.2 describes how to define a production cut. The same region can be assigned to more than one root logical volume, and root logical volumes can be removed from an existing region. A logical volume can have only *one* region assigned to it. Regions will be automatically registered in a store which will take care of destroying them at the end of the job. A default region with a default production cut is automatically created and assigned to the world volume.

Regions can also become 'envelopes' for fast-simulation; can be assigned user-limits or generic user-information (`G4VUserRegionInformation`); can be associated to specific stepping-actions (`G4UserSteppingAction`) or have assigned a local magnetic-field (local fields specifically associated to logical volumes take precedence anyhow).

4.1.4. Physical Volumes

Physical volumes represent the spatial positioning of the volumes describing the detector elements. Several techniques can be used. They range from the simple placement of a single copy to the repeated positioning using either a simple linear formula or a user specified function.

The simple placement involves the definition of a transformation matrix for the volume to be positioned. Repeated positioning is defined using the number of times a volume should be replicated at a given distance along a given direction. Finally it is possible to define a parameterised formula to specify the position of multiple copies of a volume. Details about these methods are given below.

Note - For geometries which vary between runs and for which components of the old geometry setup are explicitely -deleted-, it is required to consider the proper order of deletion (which is the exact inverse of the actual construction, i.e., first delete physical volumes and then logical volumes). Deleting a logical volume does NOT delete its daughter volumes.

It is not necessary to delete the geometry setup at the end of a job, the system will take care to free the volume and solid stores at the end of the job. The user has to take care of the deletion of any additional transformation or rotation matrices allocated dinamically in his/her own application.

4.1.4.1. Placements: single positioned copy

In this case, the Physical Volume is created by associating a Logical Volume with a Rotation Matrix and a Translation vector. The Rotation Matrix represents the rotation of the reference frame of the considered volume relatively to its mother volume's reference frame. The Translation Vector represents the translation of the current volume in the reference frame of its mother volume.

Transformations including reflections are not allowed.

To create a Placement one must construct it using:

```
G4PVPlacement(       G4RotationMatrix*  pRot,
              const  G4ThreeVector&     tlate,
                     G4LogicalVolume*   pCurrentLogical,
              const  G4String&          pName,
                     G4LogicalVolume*   pMotherLogical,
                     G4bool             pMany,
                     G4int              pCopyNo,
                     G4bool             pSurfChk=false )
```

where:

`pRot`	Rotation with respect to its mother volume
`tlate`	Translation with respect to its mother volume
`pCurrentLogical`	The associated Logical Volume
`pName`	String identifier for this placement
`pMotherLogical`	The associated mother volume
`pMany`	For future use. Can be set to false
`pCopyNo`	Integer which identifies this placement
`pSurfChk`	if true activates check for overlaps with existing volumes

Care must be taken because the rotation matrix is not copied by a `G4PVPlacement`. So the user must not modify it after creating a Placement that uses it. However the same rotation matrix can be re-used for many volumes.

Currently Boolean operations are not implemented at the level of physical volume. So `pMany` must be false. However, an alternative implementation of Boolean operations exists. In this approach a solid can be created from the union, intersection or subtraction of two solids. See Section 4.1.2.2 above for an explanation of this.

The mother volume must be specified for all volumes *except* the world volume.

An alternative way to specify a Placement utilizes a different method to place the volume. The solid itself is moved by rotating and translating it to bring it into the system of coordinates of the mother volume. This *active* method can be utilized using the following constructor:

```
G4PVPlacement(       G4Transform3D      solidTransform,
                     G4LogicalVolume*   pCurrentLogical,
               const G4String&          pName,
                     G4LogicalVolume*   pMotherLogical,
                     G4bool             pMany,
                     G4int              pCopyNo,
                     G4bool             pSurfChk=false )
```

An alternative method to specify the mother volume is to specify its placed physical volume. It can be used in either of the above methods of specifying the placement's position and rotation. The effect will be exactly the same as for using the mother logical volume.

Note that a Placement Volume can still represent multiple detector elements. This can happen if several copies exist of the mother logical volume. Then different detector elements will belong to different branches of the tree of the hierarchy of geometrical volumes.

4.1.4.2. Repeated volumes

In this case, a single Physical Volume represents multiple copies of a volume within its mother volume, allowing to save memory. This is normally done when the volumes to be positioned follow a well defined rotational or translational symmetry along a Cartesian or cylindrical coordinate. The Repeated Volumes technique is available for volumes described by CSG solids.

Replicas:

Replicas are *repeated volumes* in the case when the multiple copies of the volume are all identical. The coordinate axis and the number of replicas need to be specified for the program to compute at run time the transformation matrix corresponding to each copy.

```
G4PVReplica( const G4String&          pName,
                   G4LogicalVolume*   pCurrentLogical,
                   G4LogicalVolume*   pMotherLogical, // OR G4VPhysicalVolume*
             const EAxis              pAxis,
             const G4int              nReplicas,
             const G4double           width,
             const G4double           offset=0 )
```

where:

`pName`	String identifier for the replicated volume
`pCurrentLogical`	The associated Logical Volume
`pMotherLogical`	The associated mother volume
`pAxis`	The axis along with the replication is applied
`nReplicas`	The number of replicated volumes
`width`	The width of a single replica along the axis of replication
`offset`	Possible offset associated to mother offset along the axis of replication

`G4PVReplica` represents `nReplicas` volumes differing only in their positioning, and completely **filling** the containing mother volume. Consequently if a `G4PVReplica` is 'positioned' inside a given mother it **MUST** be the

mother's only daughter volume. Replica's correspond to divisions or slices that completely fill the mother volume and have no offsets. For Cartesian axes, slices are considered perpendicular to the axis of replication.

The replica's positions are calculated by means of a linear formula. Replication may occur along:

- *Cartesian axes* `(kXAxis,kYAxis,kZAxis)`

  The replications, of specified width have coordinates of form `(-width*(nReplicas-1)*0.5+n*width,0,0)`

  where `n=0.. nReplicas-1` for the case of `kXAxis`, and are unrotated.
- *Radial axis (cylindrical polar)* `(kRho)`

  The replications are cons/tubs sections, centred on the origin and are unrotated.

  They have radii of `width*n+offset` to `width*(n+1)+offset` where `n=0..nReplicas-1`
- *Phi axis (cylindrical polar)* `(kPhi)`

  The replications are *phi sections* or *wedges*, and of cons/tubs form.

  They have `phi` of `offset+n*width` to `offset+(n+1)*width` where `n=0..nReplicas-1`

The coordinate system of the replicas is at the centre of each replica for the cartesian axis. For the radial case, the coordinate system is unchanged from the mother. For the `phi` axis, the new coordinate system is rotated such that the X axis bisects the angle made by each wedge, and Z remains parallel to the mother's Z axis.

The solid associated via the replicas' logical volume should have the dimensions of the first volume created and must be of the correct symmetry/type, in order to assist in good visualisation.

ex. For X axis replicas in a box, the solid should be another box with the dimensions of the replications. (same Y & Z dimensions as mother box, X dimension = mother's X dimension/nReplicas).

Replicas may be placed inside other replicas, provided the above rule is observed. Normal placement volumes may be placed inside replicas, provided that they do not intersect the mother's or any previous replica's boundaries. Parameterised volumes may not be placed inside.

Because of these rules, it is not possible to place any other volume inside a replication in `radius`.

The world volume *cannot* act as a replica, therefore it cannot be sliced.

During tracking, the translation + rotation associated with each `G4PVReplica` object is modified according to the currently 'active' replication. The solid is not modified and consequently has the wrong parameters for the cases of `phi` and `r` replication and for when the cross-section of the mother is not constant along the replication.

Example:

Example 4.2. An example of simple replicated volumes with `G4PVReplica`.

```
G4PVReplica repX("Linear Array",
                 pRepLogical,
                 pContainingMother,
                 kXAxis, 5, 10*mm);

G4PVReplica repR("RSlices",
                 pRepRLogical,
                 pContainingMother,
                 kRho, 5, 10*mm, 0);

G4PVReplica repRZ("RZSlices",
                  pRepRZLogical,
                  &repR,
                  kZAxis, 5, 10*mm);

G4PVReplica repRZPhi("RZPhiSlices",
                     pRepRZPhiLogical,
                     &repRZ,
                     kPhi, 4, M_PI*0.5*rad, 0);
```

`RepX` is an array of 5 replicas of width 10*mm, positioned inside and completely filling the volume pointed by `pContainingMother`. The mother's X length must be 5*10*mm=50*mm (for example, if the mother's solid were a Box of half lengths [25,25,25] then the replica's solid must be a box of half lengths [25,25,5]).

If the containing mother's solid is a tube of radius 50*mm and half Z length of 25*mm, `RepR` divides the mother tube into 5 cylinders (hence the solid associated with `pRepRLogical` must be a tube of radius 10*mm, and half Z length 25*mm); `repRZ` divides it into 5 shorter cylinders (the solid associated with `pRepRZLogical` must be a tube of radius 10*mm, and half Z length 5*mm); finally, `repRZPhi` divides it into 4 tube segments with full angle of 90 degrees (the solid associated with `pRepRZPhiLogical` must be a tube segment of radius 10*mm, half Z length 5*mm and delta phi of M_PI*0.5*rad).

No further volumes may be placed inside these replicas. To do so would result in intersecting boundaries due to the `r` replications.

Parameterised Volumes:

Parameterised Volumes are *repeated volumes* in the case in which the multiple copies of a volume can be different in size, solid type, or material. The solid's type, its dimensions, the material and the transformation matrix can all be parameterised in function of the copy number, both when a strong symmetry exist and when it does not. The user implements the desired parameterisation function and the program computes and updates automatically at run time the information associated to the Physical Volume.

An example of creating a parameterised volume (by dimension and position) exists in novice example N02. The implementation is provided in the two classes `ExN02DetectorConstruction` and `ExN02ChamberParameterisation`.

To create a parameterised volume, one must first create its logical volume like `trackerChamberLV` below. Then one must create his own parameterisation class (*ExN02ChamberParameterisation*) and instantiate an object of this class (`chamberParam`). We will see how to create the parameterisation below.

Example 4.3. An example of Parameterised volumes.

```
//------------------------------
// Tracker segments
//------------------------------
// An example of Parameterised volumes
// dummy values for G4Box -- modified by parameterised volume
G4VSolid * solidChamber =
             new G4Box("chamberBox", 10.*cm, 10.*cm, 10.*cm);

G4LogicalVolume * trackerChamberLV
  = new G4LogicalVolume(solidChamber, Aluminum, "trackerChamberLV");
G4VPVParameterisation * chamberParam
  = new ExN02ChamberParameterisation(
                        6,           //  NoChambers,
                       -240.*cm,     //  Z of centre of first
                       80*cm,        //  Z spacing of centres
                       20*cm,        //  Width Chamber,
                       50*cm,        //  lengthInitial,
                       trackerSize*2.); //  lengthFinal

G4VPhysicalVolume *trackerChamber_phys
  = new G4PVParameterised("TrackerChamber_parameterisedPV",
                      trackerChamberLV, // Its logical volume
                      logicTracker,     // Mother logical volume
                      kUndefined,       // Allow default voxelising -- no axis
                      6,                // Number of chambers
                      chamberParam);    // The parameterisation
// "kUndefined" is the suggested choice, giving 3D voxelisation (i.e. along the three
// cartesian axes, as is applied for placements.
//
// Note:  In some cases where volume have clear separation along a single axis,
// this axis (eg kZAxis) can be used to choose (force) optimisation only along
// this axis in geometrical calculations.
// When an axis is given it forces the use of one-dimensional voxelisation.
```

The general constructor is:

```
   G4PVParameterised( const G4String&              pName,
                      G4LogicalVolume*       pCurrentLogical,
                      G4LogicalVolume*       pMotherLogical, // OR G4VPhysicalVolume*
                    const EAxis                  pAxis,
                    const G4int                  nReplicas,
                      G4VPVParameterisation* pParam,
                      G4bool                 pSurfChk=false )
```

Note that for a parameterised volume the user must always specify a mother volume. So the world volume can *never* be a parameterised volume, nor it can be sliced. The mother volume can be specified either as a physical or a logical volume.

`pAxis` specifies the tracking optimisation algorithm to apply: if a valid axis (the axis along which the parameterisation is performed) is specified, a simple one-dimensional voxelisation algorithm is applied; if "kUndefined" is specified instead, the default three-dimensional voxelisation algorithm applied for normal placements will be activated. In the latter case, more voxels will be generated, therefore a greater amount of memory will be consumed by the optimisation algorithm.

`pSurfChk` if `true` activates a check for overlaps with existing volumes or paramaterised instances.

The parameterisation mechanism associated to a parameterised volume is defined in the parameterisation class and its methods. Every parameterisation must create two methods:

- `ComputeTransformation` defines where one of the copies is placed,
- `ComputeDimensions` defines the size of one copy, and
- a constructor that initializes any member variables that are required.

An example is `ExN02ChamberParameterisation` that parameterises a series of boxes of different sizes

Example 4.4. An example of Parameterised boxes of different sizes.

```
class ExN02ChamberParameterisation : public G4VPVParameterisation
{
  ...
  void ComputeTransformation(const G4int       copyNo,
                             G4VPhysicalVolume *physVol) const;

  void ComputeDimensions(G4Box&              trackerLayer,
                         const G4int             copyNo,
                         const G4VPhysicalVolume *physVol) const;
  ...
}
```

These methods works as follows:

The `ComputeTransformation` method is called with a copy number for the instance of the parameterisation under consideration. It must compute the transformation for this copy, and set the physical volume to utilize this transformation:

```
void ExN02ChamberParameterisation::ComputeTransformation
(const G4int copyNo,G4VPhysicalVolume *physVol) const
{
  G4double      Zposition= fStartZ + copyNo * fSpacing;
  G4ThreeVector origin(0,0,Zposition);
  physVol->SetTranslation(origin);
  physVol->SetRotation(0);
}
```

Note that the translation and rotation given in this scheme are those for the frame of coordinates (the *passive* method). They are **not** for the *active* method, in which the solid is rotated into the mother frame of coordinates.

Similarly the `ComputeDimensions` method is used to set the size of that copy.

```
void ExN02ChamberParameterisation::ComputeDimensions
(G4Box & trackerChamber, const G4int copyNo,
 const G4VPhysicalVolume * physVol) const
{
  G4double  halfLength= fHalfLengthFirst + (copyNo-1) * fHalfLengthIncr;
  trackerChamber.SetXHalfLength(halfLength);
  trackerChamber.SetYHalfLength(halfLength);
  trackerChamber.SetZHalfLength(fHalfWidth);
}
```

The user must ensure that the type of the first argument of this method (in this example `G4Box &`) corresponds to the type of object the user give to the logical volume of parameterised physical volume.

More advanced usage allows the user:

- to change the type of solid by creating a `ComputeSolid` method, or
- to change the material of the volume by creating a `ComputeMaterial` method. This method can also utilise information from a parent or other ancestor volume (see the Nested Parameterisation below.)

for the parameterisation.

Example N07 shows a simple parameterisation by material. A more complex example is provided in `examples/extended/medical/DICOM`, where a phantom grid of cells is built using a parameterisation by material defined through a map.

Note

Currently for many cases it is not possible to add daughter volumes to a parameterised volume. Only parameterised volumes all of whose solids have the same size are allowed to contain daughter volumes. When the size or type of solid varies, adding daughters is not supported. So the full power of parameterised volumes can be used only for "leaf" volumes, which contain no other volumes.

A hierarchy of volumes included in a parameterised volume cannot vary. Therefore, it is not possible to implement a parameterisation which can modify the hierachy of volumes included inside a specific parameterised copy.

Advanced parameterisations for 'nested' parameterised volumes

A new type of parameterisation enables a user to have the daughter's material also depend on the copy number of the parent when a parameterised volume (daughter) is located inside another (parent) repeated volume. The parent volume can be a replica, a parameterised volume, or a division if the key feature of modifying its contents is utilised. (Note: a 'nested' parameterisation inside a placement volume is not supported, because all copies of a placement volume must be identical at all levels.)

In such a " nested" parameterisation , the user must provide a `ComputeMaterial` method that utilises the new argument that represents the touchable history of the parent volume:

```
// Sample Parameterisation
class SampleNestedParameterisation : public G4VNestedParameterisation
{
 public:
   // .. other methods ...
    // Mandatory method, required and reason for this class
    virtual G4Material* ComputeMaterial(G4VPhysicalVolume *currentVol,
                                                          const G4int no_lev,
                                                          const G4VTouchable *parentTouch);
 private:
    G4Material *material1, *material2;
};
```

The implementation of the method can utilise any information from a parent or other ancestor volume of its parameterised physical volume, but typically it will use only the copy number:

```
G4Material*
```

```
SampleNestedParameterisation::ComputeMaterial(G4VPhysicalVolume *currentVol,
                                              const G4int no_lev,
                                              const G4VTouchable *parentTouchable)
{
   G4Material *material=0;

   // Get the information about the parent volume
   G4int no_parent= parentTouchable->GetReplicaNumber();
   G4int no_total= no_parent + no_lev;
   // A simple 'checkerboard' pattern of two materials
   if( no_total / 2 == 1 ) material= material1;
   else  material= material2;
   // Set the material to the current logical volume
   G4LogicalVolume* currentLogVol= currentVol->GetLogicalVolume();
   currentLogVol->SetMaterial( material );
   return material;
}
```

Nested parameterisations are suitable for the case of regular, 'voxel' geometries in which a large number of 'equal' volumes are required, and their only difference is in their material. By creating two (or more) levels of parameterised physical volumes it is possible to divide space, while requiring only limited additional memory for very fine-level optimisation. This provides fast navigation. Alternative implementations, taking into account the regular structure of such geometries in navigation are under study.

Divisions of Volumes

Divisions in Geant4 are implemented as a specialized type of parameterised volumes.

They serve to divide a volume into identical copies along one of its axes, providing the possibility to define an *offset*, and without the limitation that the daugthers have to fill the mother volume as it is the case for the replicas. In the case, for example, of a tube divided along its radial axis, the copies are not strictly identical, but have increasing radii, although their widths are constant.

To divide a volume it will be necessary to provide:

1. the axis of division, and
2. either
   - the number of divisions (so that the width of each division will be automatically calculated), or
   - the division width (so that the number of divisions will be automatically calculated to fill as much of the mother as possible), or
   - both the number of divisions and the division width (this is especially designed for the case where the copies do not fully fill the mother).

An *offset* can be defined so that the first copy will start at some distance from the mother wall. The dividing copies will be then distributed to occupy the rest of the volume.

There are three constructors, corresponding to the three input possibilities described above:

- Giving only the number of divisions:

```
    G4PVDivision( const G4String& pName,
                        G4LogicalVolume* pCurrentLogical,
                        G4LogicalVolume* pMotherLogical,
                  const EAxis pAxis,
                  const G4int nDivisions,
                  const G4double offset )
```

- Giving only the division width:

```
    G4PVDivision( const G4String& pName,
                        G4LogicalVolume* pCurrentLogical,
                        G4LogicalVolume* pMotherLogical,
                  const EAxis pAxis,
                  const G4double width,
                  const G4double offset )
```

- Giving the number of divisions and the division width:

```
G4PVDivision( const G4String& pName,
                    G4LogicalVolume* pCurrentLogical,
                    G4LogicalVolume* pMotherLogical,
              const EAxis pAxis,
              const G4int nDivisions,
              const G4double width,
              const G4double offset )
```

where:

`pName`	String identifier for the replicated volume
`pCurrentLogical`	The associated Logical Volume
`pMotherLogical`	The associated mother Logical Volume
`pAxis`	The axis along which the division is applied
`nDivisions`	The number of divisions
`width`	The width of a single division along the axis
`offset`	Possible offset associated to the mother along the axis of division

The parameterisation is calculated automatically using the values provided in input. Therefore the dimensions of the solid associated with `pCurrentLogical` will not be used, but recomputed through the `G4VParameterisation::ComputeDimension()` method.

Since `G4VPVParameterisation` may have different `ComputeDimension()` methods for each solid type, the user must provide a solid that is of the same type as of the one associated to the mother volume.

As for any replica, the coordinate system of the divisions is related to the centre of each division for the cartesian axis. For the radial axis, the coordinate system is the same of the mother volume. For the phi axis, the new coordinate system is rotated such that the X axis bisects the angle made by each wedge, and Z remains parallel to the mother's Z axis.

As divisions are parameterised volumes with constant dimensions, they may be placed inside other divisions, except in the case of divisions along the radial axis.

It is also possible to place other volumes inside a volume where a division is placed.

The list of volumes that currently support divisioning and the possible division axis are summarised below:

`G4Box`	`kXAxis`, `kYAxis`, `kZAxis`
`G4Tubs`	`kRho`, `kPhi`, `kZAxis`
`G4Cons`	`kRho`, `kPhi`, `kZAxis`
`G4Trd`	`kXAxis`, `kYAxis`, `kZAxis`
`G4Para`	`kXAxis`, `kYAxis`, `kZAxis`
`G4Polycone`	`kRho`, `kPhi`, `kZAxis`
`G4Polyhedra`	`kRho`, `kPhi`, `kZAxis` (*)

(*) - `G4Polyhedra`:

- `kPhi` - the number of divisions has to be the same as solid sides, (i.e. `numSides`), the width will *not* be taken into account.

In the case of division along `kRho` of `G4Cons`, `G4Polycone`, `G4Polyhedra`, if width is provided, it is taken as the width at the `-Z` radius; the width at other radii will be scaled to this one.

Examples are given below in listings Example 4.4 and Example 4.5.

Example 4.5. An example of a box division along different axes, with or without offset.

```
G4Box* motherSolid = new G4Box("motherSolid", 0.5*m, 0.5*m, 0.5*m);
G4LogicalVolume* motherLog = new G4LogicalVolume(motherSolid, material, "mother",0,0,0);
G4Para* divSolid = new G4Para("divSolid", 0.512*m, 1.21*m, 1.43*m);
G4LogicalVolume* childLog = new G4LogicalVolume(divSolid, material, "child",0,0,0);

G4PVDivision divBox1("division along X giving nDiv",
                     childLog, motherLog, kXAxis, 5, 0.);

G4PVDivision divBox2("division along X giving width and offset",
                     childLog, motherLog, kXAxis, 0.1*m, 0.45*m);

G4PVDivision divBox3("division along X giving nDiv, width and offset",
                     childLog, motherLog, kXAxis, 3, 0.1*m, 0.5*m);
```

- `divBox1` is a division of a box along its `X` axis in 5 equal copies. Each copy will have a dimension in meters of `[0.2, 1., 1.]`.
- `divBox2` is a division of the same box along its `X` axis with a width of `0.1` meters and an offset of `0.5` meters. As the mother dimension along `X` of `1` meter (`0.5*m` of halflength), the division will be sized in total `1 - 0.45 = 0.55` meters. Therefore, there's space for 5 copies, the first extending from `-0.05` to `0.05` meters in the mother's frame and the last from `0.35` to `0.45` meters.
- `divBox3` is a division of the same box along its `X` axis in 3 equal copies of width `0.1` meters and an offset of `0.5` meters. The first copy will extend from `0.` to `0.1` meters in the mother's frame and the last from `0.2` to `0.3` meters.

Example 4.6. An example of division of a polycone.

```
G4double* zPlanem = new G4double[3];
          zPlanem[0]= -1.*m;
          zPlanem[1]= -0.25*m;
          zPlanem[2]=  1.*m;
G4double* rInnerm = new G4double[3];
          rInnerm[0]=0.;
          rInnerm[1]=0.1*m;
          rInnerm[2]=0.5*m;
G4double* rOuterm  = new G4double[3];
          rOuterm[0]=0.2*m;
          rOuterm[1]=0.4*m;
          rOuterm[2]=1.*m;
G4Polycone* motherSolid = new G4Polycone("motherSolid", 20.*deg, 180.*deg,
                                         3, zPlanem, rInnerm, rOuterm);
G4LogicalVolume* motherLog = new G4LogicalVolume(motherSolid, material, "mother",0,0,0);

G4double* zPlaned = new G4double[3];
          zPlaned[0]= -3.*m;
          zPlaned[1]= -0.*m;
          zPlaned[2]=  1.*m;
G4double* rInnerd = new G4double[3];
          rInnerd[0]=0.2;
          rInnerd[1]=0.4*m;
          rInnerd[2]=0.5*m;
G4double* rOuterd  = new G4double[3];
          rOuterd[0]=0.5*m;
          rOuterd[1]=0.8*m;
          rOuterd[2]=2.*m;
G4Polycone* divSolid = new G4Polycone("divSolid", 0.*deg, 10.*deg,
                                      3, zPlaned, rInnerd, rOuterd);
G4LogicalVolume* childLog = new G4LogicalVolume(divSolid, material, "child",0,0,0);

G4PVDivision divPconePhiW("division along phi giving width and offset",
                          childLog, motherLog, kPhi, 30.*deg, 60.*deg);

G4PVDivision divPconeZN("division along Z giving nDiv and offset",
                        childLog, motherLog, kZAxis, 2, 0.1*m);
```

- `divPconePhiW` is a division of a polycone along its `phi` axis in equal copies of width 30 degrees with an offset of 60 degrees. As the mother extends from 0 to 180 degrees, there's space for 4 copies. All the copies

have a starting angle of 20 degrees (as for the mother) and a `phi` extension of 30 degrees. They are rotated around the `Z` axis by 60 and 30 degrees, so that the first copy will extend from 80 to 110 and the last from 170 to 200 degrees.
- `divPconeZN` is a division of the same polycone along its `Z` axis. As the mother polycone has two sections, it will be divided in two one-section polycones, the first one extending from -1 to -0.25 meters, the second from -0.25 to 1 meters. Although specified, the offset will not be used.

4.1.5. Touchables: Uniquely Identifying a Volume

4.1.5.1. Introduction to Touchables

A *touchable* for a volume serves the purpose of providing a unique identification for a detector element. This can be useful for description of the geometry alternative to the one used by the Geant4 tracking system, such as a Sensitive Detectors based read-out geometry, or a parameterised geometry for fast Monte Carlo. In order to create a *touchable volume*, several techniques can be implemented: for example, in Geant4 touchables are implemented as solids associated to a transformation-matrix in the global reference system, or as a hierarchy of physical volumes up to the root of the geometrical tree.

A touchable is a geometrical entity (volume or solid) which has a unique placement in a detector description. It is represented by an abstract base class which can be implemented in a variety of ways. Each way must provide the capabilities of obtaining the transformation and solid that is described by the touchable.

4.1.5.2. What can a Touchable do?

All `G4VTouchable` implementations must respond to the two following "requests", where in all cases, by `depth` it is meant the number of levels *up* in the tree to be considered (the default and current one is `0`):

1. `GetTranslation(depth)`
2. `GetRotation(depth)`

that return the components of the volume's transformation.

Additional capabilities are available from implementations with more information. These have a default implementation that causes an exception.

Several capabilities are available from touchables with physical volumes:

3. `GetSolid(depth)` gives the solid associated to the touchable.

4. `GetVolume(depth)` gives the physical volume.

5. `GetReplicaNumber(depth)` or `GetCopyNumber(depth)` which return the copy number of the physical volume (replicated or not).

Touchables that store volume hierarchy (history) have the whole stack of parent volumes available. Thus it is possible to add a little more state in order to extend its functionality. We add a "pointer" to a level and a member function to move the level in this stack. Then calling the above member functions for another level the information for that level can be retrieved.

The top of the history tree is, by convention, the world volume.

6. `GetHistoryDepth()` gives the depth of the history tree.

7. `MoveUpHistory(num)` moves the current pointer inside the touchable to point `num` levels up the history tree. Thus, e.g., calling it with `num=1` will cause the internal pointer to move to the mother of the current volume.

   WARNING: this function changes the state of the touchable and can cause errors in tracking if applied to Pre/Post step touchables.

These methods are valid only for the *touchable-history* type, as specified also below.

An update method, with different arguments is available, so that the information in a touchable can be updated:

8. `UpdateYourself(vol, history)` takes a physical volume pointer and can additionally take a `NavigationHistory` pointer.

4.1.5.3. Touchable history holds stack of geometry data

As shown in Sections Section 4.1.3 and Section 4.1.4, a logical volume represents unpositioned detector elements, and a physical volume can represent multiple detector elements. On the other hand, touchables provide a unique identification for a detector element. In particular, the Geant4 transportation process and the tracking system exploit touchables as implemented in `G4TouchableHistory`. The touchable history is the minimal set of information required to specify the full genealogy of a given physical volume (up to the root of the geometrical tree). These touchable volumes are made available to the user at every step of the Geant4 tracking in `G4VUserSteppingAction`.

To create/access a `G4TouchableHistory` the user must message `G4Navigator` which provides the method `CreateTouchableHistoryHandle()`:

```
G4TouchableHistoryHandle CreateTouchableHistoryHandle() const;
```

this will return a handle to the touchable.

The methods that differentiate the touchable-history from other touchables (since they have meaning only for this type...), are:

```
G4int GetHistoryDepth()  const;
G4int MoveUpHistory( G4int num_levels = 1 );
```

The first method is used to find out how many levels deep in the geometry tree the current volume is. The second method asks the touchable to eliminate its deepest level.

As mentioned above, `MoveUpHistory(num)` significantly modifies the state of a touchable.

4.1.6. Creating an Assembly of Volumes

`G4AssemblyVolume` is a helper class which allows several logical volumes to be combined together in an arbitrary way in 3D space. The result is a placement of a normal logical volume, but where final physical volumes are many.

However, an *assembly* volume does not act as a real mother volume, being an envelope for its daughter volumes. Its role is over at the time the placement of the logical assembly volume is done. The physical volume objects become independent copies of each of the assembled logical volumes.

This class is particularly useful when there is a need to create a regular pattern in space of a complex component which consists of different shapes and can't be obtained by using replicated volumes or parametrised volumes (see also Figure 4.2 reful usage of `G4AssemblyVolume` must be considered though, in order to avoid cases of "proliferation" of physical volumes all placed in the same mother.

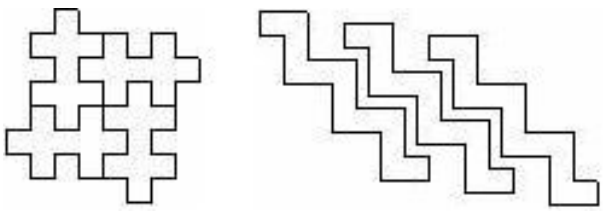


Figure 4.2. Examples of *assembly* of volumes.

4.1.6.1. Filling an assembly volume with its "daughters"

Participating logical volumes are represented as a triplet of <logical volume, translation, rotation> (`G4AssemblyTriplet` class).

The adopted approach is to place each participating logical volume with respect to the assembly's coordinate system, according to the specified translation and rotation.

4.1.6.2. Assembly volume placement

An assembly volume object is composed of a set of logical volumes; imprints of it can be made inside a mother logical volume.

Since the assembly volume class generates physical volumes during each imprint, the user has no way to specify identifiers for these. An internal counting mechanism is used to compose uniquely the names of the physical volumes created by the invoked `MakeImprint(...)` method(s).

The name for each of the physical volume is generated with the following format:

```
av_WWW_impr_XXX_YYY_ZZZ
```

where:

- **WWW** - assembly volume instance number
- **XXX** - assembly volume imprint number
- **YYY** - the name of the placed logical volume
- **ZZZ** - the logical volume index inside the assembly volume

It is however possible to access the constituent physical volumes of an assembly and eventually customise ID and copy-number.

4.1.6.3. Destruction of an assembly volume

At destruction all the generated physical volumes and associated rotation matrices of the imprints will be destroyed. A list of physical volumes created by `MakeImprint()` method is kept, in order to be able to cleanup the objects when not needed anymore. This requires the user to keep the assembly objects in memory during the whole job or during the life-time of the `G4Navigator`, logical volume store and physical volume store may keep pointers to physical volumes generated by the assembly volume.

The `MakeImprint()` method will operate correctly also on transformations including reflections and can be applied also to recursive assemblies (i.e., it is possible to generate imprints of assemblies including other assemblies). Giving `true` as the last argument of the `MakeImprint()` method, it is possible to activate the volumes overlap check for the assembly's constituents (the default is `false`).

At destruction of a `G4AssemblyVolume`, all its generated physical volumes and rotation matrices will be freed.

4.1.6.4. Example

This example shows how to use the `G4AssemblyVolume` class. It implements a layered detector where each layer consists of 4 plates.

In the code below, at first the world volume is defined, then solid and logical volume for the plate are created, followed by the definition of the assembly volume for the layer.

The assembly volume for the layer is then filled by the plates in the same way as normal physical volumes are placed inside a mother volume.

Finally the layers are placed inside the world volume as the imprints of the assembly volume (see Example 4.7).

Example 4.7. An example of usage of the `G4AssemblyVolume` class.

```
 static unsigned int layers = 5;

 void TstVADetectorConstruction::ConstructAssembly()
 {
   // Define world volume
   G4Box* WorldBox = new G4Box( "WBox", worldX/2., worldY/2., worldZ/2. );
   G4LogicalVolume*   worldLV  = new G4LogicalVolume( WorldBox, selectedMaterial, "WLog", 0, 0, 0);
   G4VPhysicalVolume* worldVol = new G4PVPlacement(0, G4ThreeVector(), "WPhys",worldLV,
                                                   0, false, 0);

   // Define a plate
   G4Box* PlateBox = new G4Box( "PlateBox", plateX/2., plateY/2., plateZ/2. );
   G4LogicalVolume* plateLV = new G4LogicalVolume( PlateBox, Pb, "PlateLV", 0, 0, 0 );

   // Define one layer as one assembly volume
   G4AssemblyVolume* assemblyDetector = new G4AssemblyVolume();

   // Rotation and translation of a plate inside the assembly
   G4RotationMatrix Ra;
   G4ThreeVector Ta;
   G4Transform3D Tr;

   // Rotation of the assembly inside the world
   G4RotationMatrix Rm;

   // Fill the assembly by the plates
   Ta.setX( caloX/4. ); Ta.setY( caloY/4. ); Ta.setZ( 0. );
   Tr = G4Transform3D(Ra,Ta);
   assemblyDetector->AddPlacedVolume( plateLV, Tr );

   Ta.setX( -1*caloX/4. ); Ta.setY( caloY/4. ); Ta.setZ( 0. );
   Tr = G4Transform3D(Ra,Ta);
   assemblyDetector->AddPlacedVolume( plateLV, Tr );

   Ta.setX( -1*caloX/4. ); Ta.setY( -1*caloY/4. ); Ta.setZ( 0. );
   Tr = G4Transform3D(Ra,Ta);
   assemblyDetector->AddPlacedVolume( plateLV, Tr );

   Ta.setX( caloX/4. ); Ta.setY( -1*caloY/4. ); Ta.setZ( 0. );
   Tr = G4Transform3D(Ra,Ta);
   assemblyDetector->AddPlacedVolume( plateLV, Tr );

   // Now instantiate the layers
   for( unsigned int i = 0; i < layers; i++ )
   {
     // Translation of the assembly inside the world
     G4ThreeVector Tm( 0,0,i*(caloZ + caloCaloOffset) - firstCaloPos );
     Tr = G4Transform3D(Rm,Tm);
     assemblyDetector->MakeImprint( worldLV, Tr );
   }
}
```

The resulting detector will look as in Figure 4.3, below:

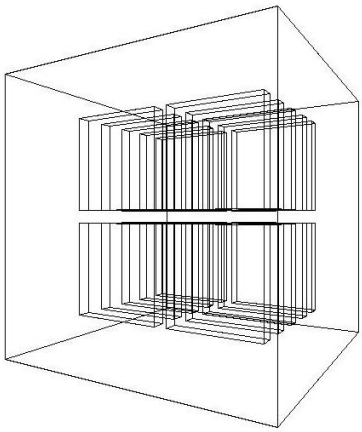


Figure 4.3. The geometry corresponding to Example 4.7.

4.1.7. Reflecting Hierarchies of Volumes

Hierarchies of volumes based on *CSG* or *specific* solids can be reflected by means of the `G4ReflectionFactory` class and `G4ReflectedSolid`, which implements a solid that has been shifted from its original reference frame to a new 'reflected' one. The reflection transformation is applied as a decomposition into rotation and translation transformations.

The factory is a singleton object which provides the following methods:

```
G4PhysicalVolumesPair Place(const G4Transform3D&   transform3D,
                            const G4String&        name,
                                  G4LogicalVolume* LV,
                                  G4LogicalVolume* motherLV,
                                  G4bool           isMany,
                                  G4int            copyNo,
                                  G4bool           surfCheck=false)

G4PhysicalVolumesPair Replicate(const G4String&        name,
                                      G4LogicalVolume* LV,
                                      G4LogicalVolume* motherLV,
                                      EAxis            axis,
                                      G4int            nofReplicas,
                                      G4double         width,
                                      G4double         offset=0)

G4PhysicalVolumesPair Divide(const G4String&        name,
                                   G4LogicalVolume* LV,
                                   G4LogicalVolume* motherLV,
                                   EAxis            axis,
                                   G4int            nofDivisions,
                                   G4double         width,
                                   G4double         offset);
```

The method `Place()` used for placements, evaluates the passed transformation. In case the transformation contains a reflection, the factory will act as follows:

1. Performs the transformation decomposition.
2. Creates a new reflected solid and logical volume, or retrieves them from a map if the reflected object was already created.
3. Transforms the daughters (if any) and place them in the given mother.

If successful, the result is a pair of physical volumes, where the second physical volume is a placement in a reflected mother. Optionally, it is also possible to force the overlaps check at the time of placement, by activating the `surfCheck` flag.

The method `Replicate()` creates replicas in the given mother. If successful, the result is a pair of physical volumes, where the second physical volume is a replica in a reflected mother.

The method `Divide()` creates divisions in the given mother. If successful, the result is a pair of physical volumes, where the second physical volume is a division in a reflected mother. There exists also two more variants of this method which may specify or not width or number of divisions.

Notes

- In order to reflect hierarchies containing divided volumes, it is necessary to explicitely instantiate a concrete *division* factory -before- applying the actual reflection: (i.e. - `G4PVDivisionFactory::GetInstance();`).
- Reflection of generic parameterised volumes is not possible yet.

Example 4.8. An example of usage of the `G4ReflectionFactory` class.

```
#include "G4ReflectionFactory.hh"

// Calor placement with rotation

G4double calThickness = 100*cm;
G4double Xpos = calThickness*1.5;
G4RotationMatrix* rotD3 = new G4RotationMatrix();
rotD3->rotateY(10.*deg);

G4VPhysicalVolume* physiCalor =
    new G4PVPlacement(rotD3,                    // rotation
                      G4ThreeVector(Xpos,0.,0.), // at (Xpos,0,0)
                      logicCalor,     // its logical volume (defined elsewhere)
                      "Calorimeter",  // its name
                      logicHall,      // its mother volume (defined elsewhere)
                      false,          // no boolean operation
                      0);             // copy number

// Calor reflection with rotation
//
G4Translate3D translation(-Xpos, 0., 0.);
G4Transform3D rotation = G4Rotate3D(*rotD3);
G4ReflectX3D  reflection;
G4Transform3D transform = translation*rotation*reflection;

G4ReflectionFactory::Instance()
         ->Place(transform,     // the transformation with reflection
                 "Calorimeter", // the actual name
                 logicCalor,    // the logical volume
                 logicHall,     // the mother volume
                 false,         // no boolean operation
                 1,             // copy number
                 false);        // no overlap check triggered

// Replicate layers
//
G4ReflectionFactory::Instance()
         ->Replicate("Layer",    // layer name
                     logicLayer, // layer logical volume (defined elsewhere)
                     logicCalor, // its mother
                     kXAxis,     // axis of replication
                     5,          // number of replica
                     20*cm);     // width of replica
```

4.1.8. The Geometry Navigator

Navigation through the geometry at tracking time is implemented by the class `G4Navigator`. The navigator is used to locate points in the geometry and compute distances to geometry boundaries. At tracking time, the navigator is intended to be the only point of interaction with tracking.

Internally, the G4Navigator has several private helper/utility classes:

- **G4NavigationHistory** - stores the compounded transformations, replication/parameterisation information, and volume pointers at each level of the hierarchy to the current location. The volume types at each level are also stored - whether normal (placement), replicated or parameterised.

- **G4NormalNavigation** - provides location & distance computation functions for geometries containing 'placement' volumes, with no voxels.
- **G4VoxelNavigation** - provides location and distance computation functions for geometries containing 'placement' physical volumes with voxels. Internally a stack of voxel information is maintained. Private functions allow for isotropic distance computation to voxel boundaries and for computation of the 'next voxel' in a specified direction.
- **G4ParameterisedNavigation** - provides location and distance computation functions for geometries containing parameterised volumes with voxels. Voxel information is maintained similarly to `G4VoxelNavigation`, but computation can also be simpler by adopting voxels to be one level deep only (*unrefined*, or 1D optimisation)
- **G4ReplicaNavigation** - provides location and distance computation functions for replicated volumes.

In addition, the navigator maintains a set of flags for exiting/entry optimisation. A navigator is not a singleton class; this is mainly to allow a design extension in future (e.g geometrical event biasing).

4.1.8.1. Navigation and Tracking

The main functions required for tracking in the geometry are described below. Additional functions are provided to return the net transformation of volumes and for the creation of touchables. None of the functions implicitly requires that the geometry be described hierarchically.

- **SetWorldVolume()**

  Sets the first volume in the hierarchy. It must be unrotated and untranslated from the origin.
- **LocateGlobalPointAndSetup()**

  Locates the volume containing the specified global point. This involves a traverse of the hierarchy, requiring the computation of compound transformations, testing replicated and parameterised volumes (etc). To improve efficiency this search may be performed relative to the last, and this is the recommended way of calling the function. A 'relative' search may be used for the first call of the function which will result in the search defaulting to a search from the root node of the hierarchy. Searches may also be performed using a `G4TouchableHistory`.
- **LocateGlobalPointAndUpdateTouchableHandle()**

  First, search the geometrical hierarchy like the above method `LocateGlobalPointAndSetup()`. Then use the volume found and its navigation history to update the touchable.
- **ComputeStep()**

  Computes the distance to the next boundary intersected along the specified unit direction from a specified point. The point must be have been located prior to calling `ComputeStep()`.

  When calling `ComputeStep()`, a proposed physics step is passed. If it can be determined that the first intersection lies at or beyond that distance then `kInfinity` is returned. In any case, if the returned step is greater than the physics step, the physics step must be taken.
- **SetGeometricallyLimitedStep()**

  Informs the navigator that the last computed step was taken in its entirety. This enables entering/exiting optimisation, and should be called prior to calling `LocateGlobalPointAndSetup()`.
- **CreateTouchableHistory()**

  Creates a `G4TouchableHistory` object, for which the caller has deletion responsibility. The 'touchable' volume is the volume returned by the last Locate operation. The object includes a copy of the current NavigationHistory, enabling the efficient relocation of points in/close to the current volume in the hierarchy.

As stated previously, the navigator makes use of utility classes to perform location and step computation functions. The different navigation utilities manipulate the `G4NavigationHistory` object.

In `LocateGlobalPointAndSetup()` the process of locating a point breaks down into three main stages - optimisation, determination that the point is contained with a subtree (mother and daughters), and determination of the actual containing daughter. The latter two can be thought of as scanning first 'up' the hierarchy until a volume that is guaranteed to contain the point is found, and then scanning 'down' until the actual volume that contains the point is found.

In `ComputeStep()` three types of computation are treated depending on the current containing volume:

- The volume contains normal (placement) daughters (or none)
- The volume contains a single parameterised volume object, representing many volumes
- The volume is a replica and contains normal (placement) daughters

4.1.8.2. Using the navigator to locate points

More than one navigator objects can be created inside an application; these navigators can act independently for different purposes. The main navigator which is "*activated* automatically at the startup of a simulation program is the navigator used for the *tracking* and attached the world volume of the main tracking (or *mass*) geometry.

The navigator for tracking can be retrieved at any state of the application by messagging the `G4TransportationManager`:

```
G4Navigator* tracking_navigator =
  G4TransportationManager::GetInstance()->GetNavigatorForTracking();
```

This also allows to retrieve at any time a pointer to the world volume assigned for tracking:

```
G4VPhysicalVolume* tracking_world = tracking_navigator->GetWorldVolume();
```

The navigator for tracking also retains all the information of the current history of volumes transversed at a precise moment of the tracking during a run. Therefore, if the navigator for tracking is used during tracking for locating a generic point in the tree of volumes, the actual particle gets also -relocated- in the specified position and tracking will be of course affected !

In order to avoid the problem above and provide information about location of a point without affecting the tracking, it is suggested to either use an alternative `G4Navigator` object (which can then be assigned to the world-volume), or access the information through the step.

Using the 'step' to retrieve geometrical information

During the tracking run, geometrical information can be retrieved through the touchable handle associated to the current step. For example, to identify the exact copy-number of a specific physical volume in the mass geometry, one should do the following:

```
// Given the pointer to the step object ...
//
G4Step* aStep = ..;

// ... retrieve the 'pre-step' point
//
G4StepPoint* preStepPoint = aStep->GetPreStepPoint();

// ... retrieve a touchable handle and access to the information
//
G4TouchableHandle theTouchable = preStepPoint->GetTouchableHandle();
G4int copyNo = theTouchable->GetCopyNumber();
G4int motherCopyNo = theTouchable->GetCopyNumber(1);
```

To determine the exact position in global coordinates in the mass geometry and convert to local coordinates (local to the current volume):

```
G4ThreeVector worldPosition = preStepPoint->GetPosition();
G4ThreeVector localPosition = theTouchable->GetHistory()->
              GetTopTransform().TransformPoint(worldPosition);
```

Using an alternative navigator to locate points

In order to know (when in the `idle` state of the application) in which physical volume a given point is located in the detector geometry, it is necessary to create an alternative navigator object first and assign it to the world volume:

```
G4Navigator* aNavigator = new G4Navigator();
aNavigator->SetWorldVolume(worldVolumePointer);
```

Then, locate the point `myPoint` (defined in global coordinates), retrieve a *touchable handle* and do whatever you need with it:

```
aNavigator->LocateGlobalPointAndSetup(myPoint);
G4TouchableHistoryHandle aTouchable =
  aNavigator->CreateTouchableHistoryHandle();

// Do whatever you need with it ...
// ... convert point in local coordinates (local to the current volume)
//
G4ThreeVector localPosition = aTouchable->GetHistory()->
              GetTopTransform().TransformPoint(myPoint);

// ... convert back to global coordinates system
G4ThreeVector globalPosition = aTouchable->GetHistory()->
              GetTopTransform().Inverse().TransformPoint(localPosition);
```

If outside of the tracking run and given a generic local position (local to a given volume in the geometry tree), it is -not- possible to determine a priori its global position and convert it to the global coordinates system. The reason for this is rather simple, nobody can guarantee that the given (local) point is located in the right -copy- of the physical volume ! In order to retrieve this information, some extra knowledge related to the absolute position of the physical volume is required first, i.e. one should first determine a global point belonging to that volume, eventually making a dedicated scan of the geometry tree through a dedicated `G4Navigator` object and then apply the method above after having created the touchable for it.

4.1.8.3. Navigation in parallel geometries

Since release 8.2 of Geant4, it is possible to define geometry trees which are `parallel` to the tracking geometry and having them assigned to navigator objects that transparently communicate in sync with the normal tracking geometry.

Parallel geometries can be defined for several uses (fast shower parameterisation, geometrical biasing, particle scoring, readout geometries, etc ...) and can *overlap* with the mass geometry defined for the tracking. The `parallel` transportation will be activated only after the registration of the parallel geometry in the detector description setup; see Section Section 4.7 for how to define a parallel geometry and register it to the run-manager.

The `G4TransportationManager` provides all the utilities to verify, retrieve and activate the navigators associated to the various parallel geometries defined.

4.1.8.4. Fast navigation in regular patterned geometries and phantoms

Since release 9.1 of Geant4, a specialised navigation algorithm has been introduced to allow for optimal memory use and extremely efficient navigation in geometries represented by a regular pattern of volumes and particularly three-dimensional grids of boxes. A typical application of this kind is the case of DICOM phantoms for medical physics studies.

The class `G4RegularNavigation` is used and automatically activated when such geometries are defined. It is required to the user to implement a parameterisation of the kind `G4PhantomParameterisation` and place the parameterised volume containing it in a container volume, so that all cells in the three-dimensional grid (*voxels*) completely fill the container volume. This way the location of a point inside a voxel can be done in a fast way, transforming the position to the coordinate system of the container volume and doing a simple calculation of the kind:

```
copyNo_x = (localPoint.x()+fVoxelHalfX*fNoVoxelX)/(fVoxelHalfX*2.)
```

where `fVoxelHalfX` is the half dimension of the voxel along `X` and `fNoVoxelX` is the number of voxels in the `X` dimension. Voxel `0` will be the one closest to the corner `(fVoxelHalfX*fNoVoxelX, fVoxelHalfY*fNoVoxelY, fVoxelHalfZ*fNoVoxelZ)`.

Having the voxels filling completely the container volume allows to avoid the lengthy computation of `ComputeStep()` and `ComputeSafety` methods required in the traditional navigation algorithm. In this case, when a track is inside the parent volume, it has always to be inside one of the voxels and it will be only necessary to calculate the distance to the walls of the current voxel.

Skipping borders of voxels with same material

Another speed optimisation can be provided by skipping the frontiers of two voxels which the same material assigned, so that bigger steps can be done. This optimisation may be not very useful when the number of materials is very big (in which case the probability of having contiguous voxels with same material is reduced), or when the physical step is small compared to the voxel dimensions (very often the case of electrons). The optimisation can be switched off in such cases, by invoking the following method with argument `skip = 0`:

Phantoms with only one material

If you want to describe a phantom of a unique material, you may spare some memory by not filling the set of indices of materials of each voxel. If the method `SetMaterialIndices()` is not invoked, the index for all voxels will be 0, that is the first (and unique) material in your list.

```
G4RegularParameterisation::SetSkipEqualMaterials( G4bool skip );
```

Example

To use the specialised navigation, it is required to first create an object of type `G4PhantomParameterisation`:

```
G4PhantomParameterisation* param = new G4PhantomParameterisation();
```

Then, fill it with the all the necessary data:

```
// Voxel dimensions in the three dimensions
//
G4double halfX = ...;
G4double halfY = ...;
G4double halfZ = ...;
param->SetVoxelDimensions( halfX, halfY, halfZ );

// Number of voxels in the three dimensions
//
G4int nVoxelX = ...;
G4int nVoxelY = ...;
G4int nVoxelZ = ...;
param->SetNoVoxel( nVoxelX, nVoxelY, nVoxelZ );

// Vector of materials of the voxels
//
std::vector < G4Material* > theMaterials;
theMaterials.push_back( new G4Material( ...
theMaterials.push_back( new G4Material( ...
param->SetMaterials( theMaterials );

// List of material indices
// For each voxel it is a number that correspond to the index of its
// material in the vector of materials defined above;
//
size_t* mateIDs = new size_t[nVoxelX*nVoxelY*nVoxelZ];
mateIDs[0] = n0;
mateIDs[1] = n1;
...
param->SetMaterialIndices( mateIDs );
```

Then, define the volume that contains all the voxels:

```
G4Box* cont_solid = new G4Box("PhantomContainer",nVoxelX*halfX.,nVoxelY*halfY.,nVoxelZ*halfZ);
G4LogicalVolume* cont_logic =
  new G4LogicalVolume( cont_solid,
  matePatient,        // material is not relevant here...
  "PhantomContainer",
  0, 0, 0 );
```

```
G4VPhysicalVolume * cont_phys =
  new G4PVPlacement(rotm,                  // rotation
      pos,                   // translation
      cont_logic,            // logical volume
      "PhantomContainer",    // name
      world_logic,           // mother volume
      false,                 // No op. bool.
      1);                    // Copy number
```

The physical volume should be assigned as the container volume of the parameterisation:

```
param->BuildContainerSolid(cont_phys);

// Assure that the voxels are completely filling the container volume
//
param->CheckVoxelsFillContainer( cont_solid->GetXHalfLength(),
                                 cont_solid->GetyHalfLength(),
                                 cont_solid->GetzHalfLength() );

// The parameterised volume which uses this parameterisation is placed
// in the container logical volume
//
G4PVParameterised * patient_phys =
  new G4PVParameterised("Patient",              // name
                        patient_logic,          // logical volume
                        cont_logic,             // mother volume
   kXAxis,                 // optimisation hint
                        nVoxelX*nVoxelY*nVoxelZ, // number of voxels
                        param);                 // parameterisation

// Indicate that this physical volume is having a regular structure
//
patient_phys->SetRegularStructureId(1);
```

An example showing the application of the optimised navigation algorithm for phantoms geometries is available in `examples/extended/medical/DICOM`. It implements a real application for reading `DICOM` images and convert them to Geant4 geometries with defined materials and densities, allowing for different implementation solutions to be chosen (non optimised, classical 3D optimisation, nested parameterisations and use of `G4PhantomParameterisation`).

4.1.8.5. Run-time commands

When running in *verbose* mode (i.e. the default, `G4VERBOSE` set while installing the Geant4 kernel libraries), the navigator provides a few commands to control its behavior. It is possible to select different verbosity levels (up to 5), with the command:

```
geometry/navigator/verbose [verbose_level]
```

or to force the navigator to run in *check* mode:

```
geometry/navigator/check_mode [true/false]
```

The latter will force more strict and less tolerant checks in step/safety computation to verify the correctness of the solids' response in the geometry.

By combining *check_mode* with verbosity level-1, additional verbosity checks on the response from the solids can be activated.

4.1.8.6. Setting Geometry Tolerance to be relative

The tolerance value defining the accuracy of tracking on the surfaces is by default set to a reasonably small value of *10E-9 mm*. Such accuracy may be however redundant for use on simulation of detectors of big size or macroscopic dimensions. Since release 9.0, it is possible to specify the surface tolerance to be relative to the extent of the world volume defined for containing the geometry setup.

The class `G4GeometryManager` can be used to activate the computation of the surface tolerance to be relative to the geometry setup which has been defined. It can be done this way:

```
G4GeometryManager::GetInstance()->SetWorldMaximumExtent(WorldExtent);
```

where, `WorldExtent` is the actual maximum extent of the world volume used for placing the whole geometry setup.

Such call to `G4GeometryManager` must be done **before** defining any geometrical component of the setup (solid shape or volume), and can be done only **once** !

The class `G4GeometryTolerance` is to be used for retrieving the actual values defined for tolerances, surface (Cartesian), angular or radial respectively:

```
G4GeometryTolerance::GetInstance()->GetSurfaceTolerance();
G4GeometryTolerance::GetInstance()->GetAngularTolerance();
G4GeometryTolerance::GetInstance()->GetRadialTolerance();
```

4.1.9. A Simple Geometry Editor

GGE is the acronym for Geant4 Graphical Geometry Editor. GGE aims to assist physicists who have a little knowledge on C++ and the Geant4 toolkit to construct his or her own detector geometry. In essence, GGE is made up of a set of tables which can contain all relevant parameters to construct a simple detector geometry. Tables for scratch or compound materials, tables for logical and physical volumes are provided. From the values in the tables, C++ source codes are automatically generated.

GGE provides methods to:

1. construct a detector geometry including `G4Element`, `G4Material`, `G4Solids`, `G4LogicalVolume`, `G4PVPlacement`, etc.
2. view the detector geometry using existing visualization system, DAWN
3. keep the detector object in a persistent way, either in GDML format (currently only logical volumes are supported) or Java serialized format.
4. produce corresponding C++ codes after the norm of Geant4 toolkit
5. make a Geant4 executable, in collaboration with another component of MOMO, i.e., GPE, or Geant4 Physics Editor.

GGE can be found in the standard Geant4 distribution under the `$G4INSTALL/environments/MOMO/MOMO.jar`. JRE (Java Run-time Environment) is prerequisite to run MOMO.jar, Java archive file of MOMO. MOMO contains GGE, GPE, GAG and other helper tools. Further information is available from the Web pages below.

MOMO = GGE + GPE + GAG: http://www-geant4.kek.jp/~yoshidah

4.1.9.1. Materials: elements and mixtures

GGE provides the database of elements in the form of the periodic table, from which users can select element(s) to construct new materials. They can be loaded, used, edited and saved as Java persistent objects or in a GDML file. In `$G4INSTALL/enviroments/MOMO`, a pre-constructed database of materials taken from the PDG book, `PDG.xml` is present.

Users can also create new materials either from scratch or by combining other materials.

- By selecting an element in the periodic table, default values as shown below are copied to a row in the table.

Use	Name	A	Z	Density	Unit	State	Temperature	Unit	Pressure	Unit

  Use marks the used materials. Only the elements and materials used in the logical volumes are kept in the detector object and are used to generate C++ constructors.
- By selecting multiple elements in the periodic table, a material from a combination of elements is assigned to a row of the compound material table. The minimum actions user have to do is to give a name to the material and define its density.

Use	Name	Elements	Density	Unit	State	Tempera-ture	Unit	Pressure Unit

By clicking the column **Elements**, a new window is open to select one of two methods:
- Add an element, giving its fraction by weight
- Add an element, giving its number of atoms.

4.1.9.2. Solids

The most popular CSG solids (`G4Box`, `G4Tubs`, `G4Cons`, `G4Trd`) and specific BREPs solids (Pcons, Pgons) are supported. All relevant parameters of such a solid can be specified in the parameter table, which pops up upon selection.

Color, or the visualization attribute of a logical volume can be created, using color chooser panel. Users can view each solid using DAWN.

4.1.9.3. Logical Volume

GGE can specify the following items:

Name	Solid	Material	VisAttribute

The lists of solid types, names of the materials defined in the material tables, and names of user-defined visualization attributes are shown automatically in respective table cell for user's choices.

The construction and assignment of appropriate entities for `G4FieldManager` and `G4VSensitiveDetector` are left to the user.

4.1.9.4. Physical Volume

Geant4 enables users to create a physical volume in different ways; the mother volume can be either a logical or a physical one, spatial rotation can be either with respect to the volume or to the frame to which the volume is attached. GGE is prepared for such four combinatorial cases to construct a physical volume.

Five simple cases of creating physical volumes are supported by GGE. Primo, a single copy of a physical volume can be created by a translation and rotation. Secondo, repeated copies can be created by repeated linear translations. A logical volume is translated in a Cartesian direction, starting from the initial position, with a given step size. Mother volume can be either another logical volume or a physical volume.

Name	Logi-calVolume	Type and name of Mother-Volume	Many	X0, Y0, Z0	Direction	StepSize	Unit	CopyNum-ber

Third, repeated copies are created by rotation around an axis, placing an object repeatedly on a ``cylindrical" pattern. Fourth, replicas are created by slicing a volume along a Cartesian direction. Fifth, replicas are created by cutting a volume cylindrically.

4.1.9.5. Generation of C++ code:

User has to type in a class name to his geometry, for example, `MyDetectorConstruction`. Then, with a mouse button click, source codes in the form of an include file and a source file are created and shown in the editor panel. In this example, they are `MyDetectorConstruction.cc` and `MyDetectorConstruction.hh` files. They reflect all current user modifications in the tables in real-time.

4.1.9.6. Visualization

The whole geometry can be visualized after the compilation of the source code `MyDetectorConstruction.cc` with appropriate parts of Geant4. (In particular only the geometry and vi-

sualization, together with the small other parts they depend on, are needed.) MOMO provides Physics Editor to create standard electromagnetic physics and a minimum main program. See the on-line document in MOMO.

4.1.10. Converting Geometries from Geant3.21

4.1.10.1. Approach

G3toG4 is the Geant4 facility to convert GEANT 3.21 geometries into Geant4. This is done in two stages:

1. The user supplies a GEANT 3.21 RZ-file (.rz) containing the initialization data structures. An executable `rztog4` reads this file and produces an ASCII *call list* file containing instructions on how to build the geometry. The source code of `rztog4` is FORTRAN.
2. A call list interpreter (`G4BuildGeom.cc`) reads these instructions and builds the geometry in the user's client code for Geant4.

4.1.10.2. Importing converted geometries into Geant4

Two examples of how to use the call list interpreter are supplied in the directory `examples/extended/g3tog4`:

1. `cltog4` is a simple example which simply invokes the call list interpreter method `G4BuildGeom` from the `G3toG4DetectorConstruction` class, builds the geometry and exits.
2. `clGeometry`, is more complete and is patterned as for the novice Geant4 examples. It also invokes the call list interpreter, but in addition, allows the geometry to be visualized and particles to be tracked.

To compile and build the G3toG4 libraries, you need to have set in your environment the variable `G4LIB_BUILD_G3TOG4` at the time of installation. The G3toG4 libraries are not built by default. Then, simply type

```
gmake
```

from the top-level `source/g3tog4` directory.

To build the converter executable `rztog4`, simply type

```
gmake bin
```

To make everything, simply type:

```
gmake global
```

To remove all `G3toG4` libraries, executables and .d files, simply type

```
gmake clean
```

4.1.10.3. Current Status

The package has been tested with the geometries from experiments like: BaBar, CMS, Atlas, Alice, Zeus, L3, and Opal.

Here is a comprehensive list of features supported and not supported or implemented in the current version of the package:

- Supported shapes: all GEANT 3.21 shapes except for `GTRA`, `CTUB`.
- `PGON`, `PCON` are built using the *specific* solids `G4Polycone` and `G4Polyhedra`.
- GEANT 3.21 `MANY` feature is only partially supported. `MANY` positions are resolved in the `G3toG4MANY()` function, which has to be processed before `G3toG4BuildTree()` (it is not called by default). In order to resolve `MANY`, the user code has to provide additional info using `G4gsbool(G4String volName, G4String manyVolName)` function for all the overlapping volumes. Daughters of overlapping volumes are then resolved automatically and should not be specified via `Gsbool`.

Limitation: a volume with a MANY position can have only this one position; if more than one position is needed a new volume has to be defined (gsvolu()) for each position.
- GSDV* routines for dividing volumes are implemented, using G4PVReplicas, for shapes:
  - BOX, TUBE, TUBS, PARA - all axes;
  - CONE, CONS - axes 2, 3;
  - TRD1, TRD2, TRAP - axis 3;
  - PGON, PCON - axis 2;
  - PARA -axis 1; axis 2,3 for a special case
- GSPOSP is implemented via individual logical volumes for each instantiation.
- GSROTM is implemented. Reflections of hierachies based on plain CSG solids are implemented through the G3Division class.
- Hits are not implemented.
- Conversion of GEANT 3.21 magnetic field is currently not supported. However, the usage of magnetic field has to be turned on.

4.1.11. Detecting Overlapping Volumes

4.1.11.1. The problem of overlapping volumes

Volumes are often positioned within other volumes with the intent that one is fully contained within the other. If, however, a volume extends beyond the boundaries of its mother volume, it is defined as overlapping. It may also be intended that volumes are positioned within the same mother volume such that they do not intersect one another. When such volumes do intersect, they are also defined as overlapping.

The problem of detecting overlaps between volumes is bounded by the complexity of the solid model description. Hence it requires the same mathematical sophistication which is needed to describe the most complex solid topology, in general. However, a tunable accuracy can be obtained by approximating the solids via first and/or second order surfaces and checking their intersections.

4.1.11.2. Detecting overlaps: built-in kernel commands

In general, the most powerful clash detection algorithms are provided by CAD systems, treating the intersection between the solids in their topological form.

Geant4 provides some built-in run-time commands to activate verification tests for the user-defined geometry:

```
geometry/test/grid_test [recursion_flag]
--> to start verification of geometry for overlapping regions
    based on standard lines grid setup. If the "recursion_flag" is
    set to 'false' (the default), the check is limited to the first
    depth level of the geometry tree; otherwise it visits recursively
    the whole geometry tree. In the latter case, it may take a long
    time, depending on the complexity of the geometry.
geometry/test/cylinder_test [recursion_flag]
--> shoots lines according to a cylindrical pattern. If the
    "recursion_flag" is set to 'false' (the default), the check is
    limited to the first depth level of the geometry tree; otherwise
    it visits recursively the whole geometry tree. In the latter case,
    it may take a long time, depending on the complexity of the geometry.
geometry/test/line_test [recursion_flag]
--> shoots a line according to a specified direction and position
    defined by the user. If the "recursion_flag" is set to 'false'
    (the default), the check is limited to the first depth level of the
    geometry tree; otherwise it visits recursively the whole geometry
    tree.
geometry/test/position
--> to specify position for the line_test.
geometry/test/direction
--> to specify direction for the line_test.
geometry/test/grid_cells
--> to define the resolution of the lines in the grid test as number
    of cells, specifying them for each dimension, X, Y and Z.
    The new settings will be applied to the grid_test command.
```

```
    geometry/test/cylinder_geometry
    --> to define the details of the cylinder geometry, by specifying:
            nPhi - number of lines per Phi
            nZ   - number of Z points
            nRho - number of Rho points
        The new settings will be applied to the cylinder_test command.
    geometry/test/cylinder_scaleZ
    --> to define the resolution of the cylinder geometry, by specifying
        the fraction scale for points along Z.
        The new settings will be applied to the cylinder_test command.
    geometry/test/cylinder_scaleRho
    --> to define the resolution of the cylinder geometry, by specifying
        the fraction scale for points along Rho.
        The new settings will be applied to the cylinder_test command.
    geometry/test/recursion_start
    --> to set the initial level in the geometry tree for starting the
        recursion (default value being zero, i.e. the world volume).
        The new settings will then be applied to any recursive test.
    geometry/test/recursion_depth
    --> to set the depth in the geometry tree for recursion, so that
        recursion will stop after having reached the specified depth (the
        default being the full depth of the geometry tree).
        The new settings will then be applied to any recursive test.
```

To detect overlapping volumes, the built-in test uses the intersection of solids with linear trajectories. For example, consider Figure 4.4:

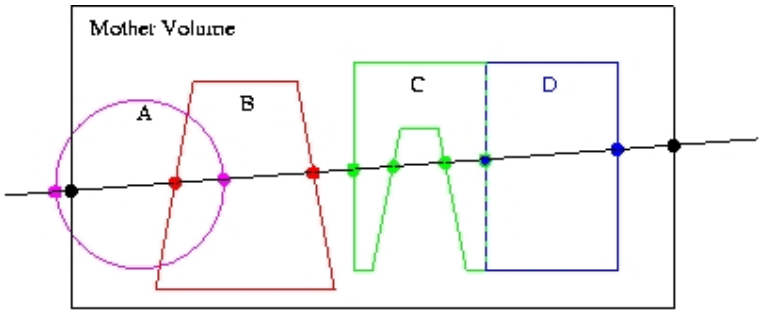


Figure 4.4. Different cases of placed volumes overlapping each other.

Here we have a line intersecting some physical volume (large, black rectangle). Belonging to the volume are four daughters: A, B, C, and D. Indicated by the dots are the intersections of the line with the mother volume and the four daughters.

This example has two geometry errors. First, volume A sticks outside its mother volume (this practice, sometimes used in GEANT3.21, is not allowed in Geant4). This can be noticed because the intersection point (leftmost magenta dot) lies outside the mother volume, as defined by the space between the two black dots.

The second error is that daughter volumes A and B overlap. This is noticeable because one of the intersections with A (rightmost magenta dot) is inside the volume B, as defined as the space between the red dots. Alternatively, one of the intersections with B (leftmost red dot) is inside the volume A, as defined as the space between the magenta dots.

Each of these two types of errors is represented by a line segment, which has a start point, an end point, and, a length. Depending on the type of error, the points are most clearly recognized in either the coordinate system of the volume, the global coordinate system, or the coordinate system of the daughters involved.

Also notice that certain errors will be missed unless a line is supplied in precisely the correct path. Unfortunately, it is hard to predict which lines are best at uncovering potential geometry errors. Instead, the geometry testing code uses a grid of lines, in the hope of at least uncovering gross geometry errors. More subtle errors could easily be missed.

Another difficult issue is roundoff error. For example, daughters C and D lie precisely next to each other. It is possible, due to roundoff, that one of the intersections points will lie just slightly inside the space of the other. In addition, a volume that lies tightly up against the outside of its mother may have an intersection point that just slightly lies outside the mother.

To avoid spurious errors caused by roundoff, a rather generous tolerance of 0.1 micron is used by default. This tolerance can be adjusted as needed by the application through the run-time command:

```
geometry/test/tolerance <new-value>
```

Finally, notice that no mention is made of the possible daughter volumes of A, B, C, and D. To keep the code simple, only the immediate daughters of a volume are checked at one pass. To test these "granddaughter" volumes, the daughters A, B, C, and D each have to be tested themselves in turn. To make this more automatic, an optional recursive algorithm is included; it first tests a target volume, then it loops over all daughter volumes and calls itself.

Pay attention! For a complex geometry, checking the entire volume hierarchy can be extremely time consuming.

4.1.11.3. Detecting overlaps at construction

Since release 8.0, the Geant4 geometry modeler provides the ability to detect overlaps of placed volumes (normal placements or parameterised) at the time of construction. This check is optional and can be activated when instantiating a placement (see `G4PVPlacement` constructor in Section 4.1.4.1) or a parameterised volume (see `G4PVParameterised` constructor in Section 4.1.4.2).

The positioning of that specific volume will be checked against all volumes in the same hierarchy level and its mother volume. Depending on the complexity of the geometry being checked, the check may require considerable CPU time; it is therefore suggested to use it only for debugging the geometry setup and to apply it only to the part of the geometry setup which requires debugging.

The classes `G4PVPlacement` and `G4PVParameterised` also provide a method:

```
G4bool CheckOverlaps(G4int res=1000, G4double tol=0., G4bool verbose=true)
```

which will force the check for the specified volume, and can be therefore used to verify for overlaps also once the geometry is fully built. The check verifies if each placed or parameterised instance is overlapping with other instances or with its mother volume. A default resolution for the number of points to be generated and verified is provided. The method returns `true` if an overlap occurs. It is also possible to specify a "tolerance" by which overlaps not exceeding such quantity will not be reported; by default, all overlaps are reported.

Using the visualization driver: DAVID

The Geant4 visualization offers a powerful debugging tool for detecting potential intersections of physical volumes. The Geant4 DAVID visualization tool can infact automatically detect the overlaps between the volumes defined in Geant4 and converted to a graphical representation for visualization purposes. The accuracy of the graphical representation can be tuned onto the exact geometrical description. In the debugging, physical-volume surfaces are automatically decomposed into 3D polygons, and intersections of the generated polygons are investigated. If a polygon intersects with another one, physical volumes which these polygons belong to are visualized in color (red is the default). The Figure 4.5 below is a sample visualization of a detector geometry with intersecting physical volumes highlighted:

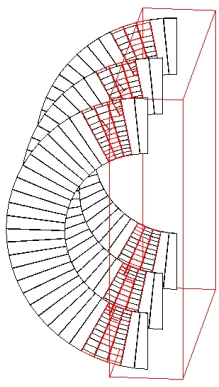


Figure 4.5. A geometry with overlapping volumes highlighted by DAVID.

At present physical volumes made of the following solids are able to be debugged: `G4Box`, `G4Cons`, `G4Para`, `G4Sphere`, `G4Trd`, `G4Trap`, `G4Tubs`. (Existence of other solids is harmless.)

Visual debugging of physical-volume surfaces is performed with the DAWNFILE driver defined in the visualization category and with the two application packages, i.e. Fukui Renderer "DAWN" and a visual intersection debugger "DAVID". DAWN and DAVID can be downloaded from the Web.

How to compile Geant4 with the DAWNFILE driver incorporated is described in Section 8.3.

If the DAWNFILE driver, DAWN and DAVID are all working well in your host machine, the visual intersection debugging of physical-volume surfaces can be performed as follows:

Run your Geant4 executable, invoke the DAWNFILE driver, and execute visualization commands to visualize your detector geometry:

```
Idle> /vis/open DAWNFILE
.....(setting camera etc)...
Idle> /vis/drawVolume
Idle> /vis/viewer/update
```

Then a file "g4.prim", which describes the detector geometry, is generated in the current directory and DAVID is invoked to read it. (The description of the format of the file g4.prim can be found from the DAWN web site documentation.)

If DAVID detects intersection of physical-volume surfaces, it automatically invokes DAWN to visualize the detector geometry with the intersected physical volumes highlighted (See the above sample visualization).

If no intersection is detected, visualization is skipped and the following message is displayed on the console:

```
-----------------------------------------------------
!!! Number of intersected volumes : 0 !!!
!!! Congratulations ! \(^o^)/         !!!
-----------------------------------------------------
```

If you always want to skip visualization, set an environmental variable as follows beforehand:

```
%  setenv DAVID_NO_VIEW  1
```

To control the precision associated to computation of intersections (default precision is set to 9), it is possible to use the environmental variable for the DAWNFILE graphics driver, as follows:

```
%  setenv G4DAWNFILE_PRECISION  10
```

If necessary, re-visualize the detector geometry with intersected parts highlighted. The data are saved in a file "g4david.prim" in the current directory. This file can be re-visualized with DAWN as follows:

```
% dawn g4david.prim
```

It is also helpful to convert the generated file g4david.prim into a VRML-formatted file and perform interactive visualization of it with your WWW browser. The file conversion tool `prim2wrml` can be downloaded from the DAWN web site download pages.

For more details, see the document of DAVID mentioned above.

4.1.11.4. Using the geometry debugging tool OLAP

OLAP is a tool developed in the CMS experiment at CERN to help in identifying ovelapping volumes in a detector geometry. It is placed in the area for specific tools/examples, in `geant4/examples/extended/geometry`. The technique consists in shooting `geantinos` particles in one direction and the opposite one, and verifying that the boundary crossings are the same.

The tool can be used for any Geant4 geometry, provided that the user geometry to be debugged is available as a subclass of `G4VUserDetectorConstruction` and is used to construct the `OlapDetConstr` class of the tool. A dummy class `RandomDetector` is provided for this purpose in the tool itself.

Run-time commands are provided by the tool to navigate in the geometry tree. UNIX like navigation of the logical volume hierarchy is provided by the `/olap/cd` command. The root of the logical volume tree can be accessed by the character '/'. Any node in the volume tree can be accessed by a '/' separated string of regular expressions. If '/' is at the beginning of the string, the tree hierarchy is transversed from the root, otherwise from the currently chosen logical volume. Further the command `/olap/goto [regexp]` can be used to jump to the first logical volume matching the expression `[regexp]`. Every successful navigation command (`/olap/cd`, `olap/goto`) results in the construction of a `NewWorld`, the mother volume being the argument of the command and the daughter volumes being the direct daughters of the mother volume.

`/olap/pwd` always shows where in the full geometrical hierarchy the current `NewWorld` and mother volume are located.

For more detailed information, view the `README` file provided with the tool.

4.1.12. Dynamic Geometry Setups

Geant4 can handle geometries which vary in time (e.g. a geometry varying between two runs in the same job).

It is considered a change to the geometry setup, whenever:

- the shape or dimension of an existing solid is modified;
- the positioning (translation or rotation) of a volume is changed;
- a volume (or a set of volumes, tree) is removed/replaced or added.

Whenever such a change happens, the geometry setup needs to be first "opened" for the change to be applied and afterwards "closed" for the optimisation to be reorganised.

In the general case, in order to notify the Geant4 system of the change in the geometry setup, the `G4RunManager` has to be messaged once the new geometry setup has been finalised:

```
    G4RunManager::GeometryHasBeenModified();
```

The above notification needs to be performed also if a material associated to a *positioned* volume is changed, in order to allow for the internal materials/cuts table to be updated. However, for relatively complex geometries the re-optimisation step may be extremely inefficient, since it has the effect that the whole geometry setup will be re-optimised and re-initialised. In cases where only a limited portion of the geometry has changed, it may be suitable to apply the re-optimisation only to the affected portion of the geometry (subtree).

Since release 7.1 of the Geant4 toolkit, it is possible to apply re-optimisation local to the subtree of the geometry which has changed. The user will have to explicitly "open/close" the geometry providing a pointer to the top physical volume concerned:

Example 4.9. Opening and closing a portion of the geometry without notifying the `G4RunManager`.

```
#include "G4GeometryManager.hh"

// Open geometry for the physical volume to be modified ...
//
G4GeometryManager::OpenGeometry(physCalor);

// Modify dimension of the solid ...
//
physCalor->GetLogicalVolume()->GetSolid()->SetXHalfLength(12.5*cm);

// Close geometry for the portion modified ...
//
G4GeometryManager::CloseGeometry(physCalor);
```

If the existing geometry setup is modified locally in more than one place, it may be convenient to apply such a technique only once, by specifying a physical volume on top of the hierarchy (subtree) containing all changed portions of the setup.

An alternative solution for dealing with dynamic geometries is to specify NOT to apply optimisation for the subtree affected by the change and apply the general solution of invoking the `G4RunManager`. In this case, a performance penalty at run-time may be observed (depending on the complexity of the not-optimised subtree), considering that, without optimisation, intersections to all volumes in the subtree will be explicitely computed each time.

4.1.13. Importing XML Models Using GDML

Geometry Description Markup Language (GDML) is a markup language based on XML and suited for the description of detector geometry models. It allows for easy exchange of geometry data in a *human-readable* XML-based description and structured formatting.

The GDML parser is a component of Geant4 which can be built and installed as an optional choice. It allows for importing and exporting GDML files, following the schema specified in the GDML documentation. The installation of the plugin is optional and requires the installation of the XercesC DOM parser.

Examples of how to import and export a detector description model based on **GDML**, and also how to extend the GDML schema, are provided and can be found in `examples/extended/persistency/gdml`.

4.1.14. Importing ASCII Text Models

Since release 9.2 of Geant4, it is also possible to import geometry setups based on a plain text description, according to a well defined syntax for identifying the different geometrical entities (solids, volumes, materials and volume attributes) with associated parameters. An example showing how to define a geometry in plain text format and import it in a Geant4 application is shown in `examples/extended/persistency/P03`. The example also covers the case of associating a sensitive detector to one of the volumes defined in the text geometry, the case of mixing C++ and text geometry definitions and the case of defining new tags in the text format so that regions and cuts by region can be defined in the text file. It also provides an example of how to write a geometry text file from the in-memory Geant4 geometry. For the details on the format see the dedicated manual.

4.1.15. Saving geometry tree objects in binary format

The Geant4 geometry tree can be stored in the Root binary file format using the *reflection* technique provided by the Reflex tool (included in Root). Such a binary file can then be used to quickly load the geometry into the memory or to move geometries between different Geant4 applications.

See Chapter 4.6 for details and references.

4.2. Material

4.2.1. General considerations

In nature, materials (chemical compounds, mixtures) are made of elements, and elements are made of isotopes. Geant4 has three main classes designed to reflect this organization. Each of these classes has a table, which is a static data member, used to keep track of the instances of the respective classes created.

G4Isotope
: This class describes the properties of atoms: atomic number, number of nucleons, mass per mole, etc.

G4Element
: This class describes the properties of elements: effective atomic number, effective number of nucleons, effective mass per mole, number of isotopes, shell energy, and quantities like cross section per atom, etc.

G4Material
: This class describes the macroscopic properties of matter: density, state, temperature, pressure, and macroscopic quantities like radiation length, mean free path, dE/dx, etc.

Only the *G4Material* class is visible to the rest of the toolkit and used by the tracking, the geometry and the physics. It contains all the information relevant to its constituent elements and isotopes, while at the same time hiding their implementation details.

4.2.2. Introduction to the Classes

4.2.2.1. G4Isotope

A *G4Isotope* object has a name, atomic number, number of nucleons, mass per mole, and an index in the table. The constructor automatically stores "this" isotope in the isotopes table, which will assign it an index number.

4.2.2.2. G4Element

A *G4Element* object has a name, symbol, effective atomic number, effective number of nucleons, effective mass of a mole, an index in the elements table, the number of isotopes, a vector of pointers to such isotopes, and a vector of relative abundances referring to such isotopes (where relative abundance means the number of atoms per volume). In addition, the class has methods to add, one by one, the isotopes which are to form the element.

A *G4Element* object can be constructed by directly providing the effective atomic number, effective number of nucleons, and effective mass of a mole, if the user explicitly wants to do so. Alternatively, a *G4Element* object can be constructed by declaring the number of isotopes of which it will be composed. The constructor will "new" a vector of pointers to *G4Isotopes* and a vector of doubles to store their relative abundances. Finally, the method to add an isotope must be invoked for each of the desired (pre-existing) isotope objects, providing their addresses and relative abundances. At the last isotope entry, the system will automatically compute the effective atomic number, effective number of nucleons and effective mass of a mole, and will store "this" element in the elements table.

A few quantities, with physical meaning or not, which are constant in a given element, are computed and stored here as "derived data members".

Using the internal Geant4 database, a *G4Element* can be accessed by atomic number or by atomic symbol ("Al", "Fe", "Pb"...). In that case *G4Element* will be found from the list of existing elements or will be constructed using data from the Geant4 database, which is derived from the NIST database of elements and isotope compositions. Thus, the natural isotope composition can be built by default. The same element can be created as using the NIST database with the natural composition of isotopes and from scratch in user code with user defined isotope composition.

4.2.2.3. G4Material

A *G4Material* object has a name, density, physical state, temperature and pressure (by default the standard conditions), the number of elements and a vector of pointers to such elements, a vector of the fraction of mass for each element, a vector of the atoms (or molecules) numbers of each element, and an index in the materials table. In addition, the class has methods to add, one by one, the elements which will comprise the material.

A *G4Material* object can be constructed by directly providing the resulting effective numbers, if the user explicitly wants to do so (an underlying element will be created with these numbers). Alternatively, a *G4Material* object can be constructed by declaring the number of elements of which it will be composed. The constructor will "new" a vector of pointers to *G4Element* and a vector of doubles to store their fraction of mass. Finally, the method to add an element must be invoked for each of the desired (pre-existing) element objects, providing their addresses and mass fractions. At the last element entry, the system will automatically compute the vector of the number of atoms of each element per volume, the total number of electrons per volume, and will store "this" material in the materials table. In the same way, a material can be constructed as a mixture of other materials and elements.

It should be noted that if the user provides the number of atoms (or molecules) for each element comprising the chemical compound, the system automatically computes the mass fraction. A few quantities, with physical meaning or not, which are constant in a given material, are computed and stored here as "derived data members".

Some materials are included in the internal Geant4 database, which were derived from the NIST database of material properties. Additionally a number of materials friquently used in HEP is included in the database. Materials are interrogated or constructed by their *names* (Section 9). There are UI commands for the material category, which provide an interactive access to the database. If material is created using the NIST database by it will consist by default of elements with the natural composition of isotopes.

4.2.2.4. Final Considerations

The classes will automatically decide if the total of the mass fractions is correct, and perform the necessary checks. The main reason why a fixed index is kept as a data member is that many cross section and energy tables will be built in the physics processes "by rows of materials (or elements, or even isotopes)". The tracking gives the physics process the address of a material object (the material of the current volume). If the material has an index according to which the cross section table has been built, then direct access is available when a number in such a table must be accessed. We get directly to the correct row, and the energy of the particle will tell us the column. Without such an index, every access to the cross section or energy tables would imply a search to get to the correct material's row. More details will be given in the section on processes.

Isotopes, elements and materials must be instantiated dynamically in the user application; they are automatically registered in internal stores and the system takes care to free the memory allocated at the end of the job.

4.2.3. Recipes for Building Elements and Materials

Example 4.10 illustrates the different ways to define materials.

Example 4.10. A program which illustrates the different ways to define materials.

```
#include "G4Isotope.hh"
#include "G4Element.hh"
#include "G4Material.hh"
#include "G4UnitsTable.hh"

int main() {
G4String name, symbol;             // a=mass of a mole;
G4double a, z, density;            // z=mean number of protons;
G4int iz, n;                       // iz=nb of protons  in an isotope;
                                   // n=nb of nucleons in an isotope;
G4int ncomponents, natoms;
G4double abundance, fractionmass;
G4double temperature, pressure;

G4UnitDefinition::BuildUnitsTable();

// define Elements
a = 1.01*g/mole;
G4Element* elH  = new G4Element(name="Hydrogen",symbol="H" , z= 1., a);

a = 12.01*g/mole;
G4Element* elC  = new G4Element(name="Carbon"  ,symbol="C" , z= 6., a);

a = 14.01*g/mole;
G4Element* elN  = new G4Element(name="Nitrogen",symbol="N" , z= 7., a);

a = 16.00*g/mole;
G4Element* elO  = new G4Element(name="Oxygen"  ,symbol="O" , z= 8., a);

a = 28.09*g/mole;
G4Element* elSi = new G4Element(name="Silicon", symbol="Si", z=14., a);

a = 55.85*g/mole;
G4Element* elFe = new G4Element(name="Iron"    ,symbol="Fe", z=26., a);

a = 183.84*g/mole;
G4Element* elW = new G4Element(name="Tungsten" ,symbol="W",  z=74., a);

a = 207.20*g/mole;
G4Element* elPb = new G4Element(name="Lead"    ,symbol="Pb", z=82., a);

// define an Element from isotopes, by relative abundance
G4Isotope* U5 = new G4Isotope(name="U235", iz=92, n=235, a=235.01*g/mole);
G4Isotope* U8 = new G4Isotope(name="U238", iz=92, n=238, a=238.03*g/mole);

G4Element* elU  = new G4Element(name="enriched Uranium", symbol="U", ncomponents=2);
elU->AddIsotope(U5, abundance= 90.*perCent);
elU->AddIsotope(U8, abundance= 10.*perCent);

cout << *(G4Isotope::GetIsotopeTable()) << endl;
cout << *(G4Element::GetElementTable()) << endl;
```

```
// define simple materials
density = 2.700*g/cm3;
a = 26.98*g/mole;
G4Material* Al = new G4Material(name="Aluminum", z=13., a, density);

density = 1.390*g/cm3;
a = 39.95*g/mole;
vG4Material* lAr = new G4Material(name="liquidArgon", z=18., a, density);

density = 8.960*g/cm3;
a = 63.55*g/mole;
G4Material* Cu = new G4Material(name="Copper"   , z=29., a, density);

// define a material from elements.   case 1: chemical molecule
density = 1.000*g/cm3;
G4Material* H2O = new G4Material(name="Water", density, ncomponents=2);
H2O->AddElement(elH, natoms=2);
H2O->AddElement(elO, natoms=1);

density = 1.032*g/cm3;
G4Material* Sci = new G4Material(name="Scintillator", density, ncomponents=2);
Sci->AddElement(elC, natoms=9);
Sci->AddElement(elH, natoms=10);

density = 2.200*g/cm3;
G4Material* SiO2 = new G4Material(name="quartz", density, ncomponents=2);
SiO2->AddElement(elSi, natoms=1);
SiO2->AddElement(elO , natoms=2);

density = 8.280*g/cm3;
G4Material* PbWO4= new G4Material(name="PbWO4", density, ncomponents=3);
PbWO4->AddElement(elO , natoms=4);
PbWO4->AddElement(elW , natoms=1);
PbWO4->AddElement(elPb, natoms=1);

// define a material from elements.   case 2: mixture by fractional mass
density = 1.290*mg/cm3;
G4Material* Air = new G4Material(name="Air  "  , density, ncomponents=2);
Air->AddElement(elN, fractionmass=0.7);
Air->AddElement(elO, fractionmass=0.3);

// define a material from elements and/or others materials (mixture of mixtures)
density = 0.200*g/cm3;
G4Material* Aerog = new G4Material(name="Aerogel", density, ncomponents=3);
Aerog->AddMaterial(SiO2, fractionmass=62.5*perCent);
Aerog->AddMaterial(H2O , fractionmass=37.4*perCent);
Aerog->AddElement (elC , fractionmass= 0.1*perCent);
```

```
// examples of gas in non STP conditions
density     = 27.*mg/cm3;
pressure    = 50.*atmosphere;
temperature = 325.*kelvin;
G4Material* CO2 = new G4Material(name="Carbonic gas", density, ncomponents=2,
                                 kStateGas,temperature,pressure);
CO2->AddElement(elC, natoms=1);
CO2->AddElement(elO, natoms=2);

density     = 0.3*mg/cm3;
pressure    = 2.*atmosphere;
temperature = 500.*kelvin;
G4Material* steam = new G4Material(name="Water steam ", density, ncomponents=1,
                                   kStateGas,temperature,pressure);
steam->AddMaterial(H2O, fractionmass=1.);

// What about vacuum ?  Vacuum is an ordinary gas with very low density
density     = universe_mean_density;               //from PhysicalConstants.h
pressure    = 1.e-19*pascal;
temperature = 0.1*kelvin;
new G4Material(name="Galactic", z=1., a=1.01*g/mole, density,
                  kStateGas,temperature,pressure);

density     = 1.e-5*g/cm3;
pressure    = 2.e-2*bar;
temperature = STP_Temperature;                     //from PhysicalConstants.h
G4Material* beam = new G4Material(name="Beam ", density, ncomponents=1,
```

```
                                      kStateGas,temperature,pressure);
beam->AddMaterial(Air, fractionmass=1.);

// print the table of materials
G4cout << *(G4Material::GetMaterialTable()) << endl;

return EXIT_SUCCESS;
}
```

As can be seen in the later examples, a material has a state: solid (the default), liquid, or gas. The constructor checks the density and automatically sets the state to gas below a given threshold (10 mg/cm3).

In the case of a gas, one may specify the temperature and pressure. The defaults are STP conditions defined in `PhysicalConstants.hh`.

An element must have the number of nucleons >= number of protons >= 1.

A material must have non-zero values of density, temperature and pressure.

Materials can also be defined using the internal Geant4 database. Example 4.11 illustrates how to do this for the same materials used in Example 4.10. There are also UI commands which allow the database to be accessed. *The list of currently avalable material names* (Section 9) is extended permanetly.

Example 4.11. A program which shows how to define materials from the internal database.

```
#include "globals.hh"
#include "G4Material.hh"
#include "G4NistManager.hh"

int main() {
  G4NistManager* man = G4NistManager::Instance();
  man->SetVerbose(1);

  // define elements
  G4Element* C  = man->FindOrBuildElement("C");
  G4Element* Pb = man->FindOrBuildMaterial("Pb");

  // define pure NIST materials
  G4Material* Al = man->FindOrBuildMaterial("G4_Al");
  G4Material* Cu = man->FindOrBuildMaterial("G4_Cu");

  // define NIST materials
  G4Material* H2O  = man->FindOrBuildMaterial("G4_WATER");
  G4Material* Sci  = man->FindOrBuildMaterial("G4_PLASTIC_SC_VINYLTOLUENE");
  G4Material* SiO2 = man->FindOrBuildMaterial("G4_SILICON_DIOXIDE");
  G4Material* Air  = man->FindOrBuildMaterial("G4_AIR");

  // HEP materials
  G4Material* PbWO4  = man->FindOrBuildMaterial("G4_PbWO4");
  G4Material* lAr    = man->FindOrBuildMaterial("G4_lAr");
  G4Material* vac    = man->FindOrBuildMaterial("G4_Galactic");

  // define gas material at non STP conditions (T = 120K, P=0.5atm)
  G4Material* coldAr = man->ConstructNewGasdMaterial("ColdAr","G4_Ar",120.*kelvin,0.5*atmosphere);

  // print the table of materials
  G4cout << *(G4Material::GetMaterialTable()) << endl;

  return EXIT_SUCCESS;
}
```

4.2.4. The Tables

4.2.4.1. Print a constituent

The following shows how to print a constituent:

```
  G4cout << elU << endl;
  G4cout << Air << endl;
```

4.2.4.2. Print the table of materials

The following shows how to print the table of materials:

```
G4cout << *(G4Material::GetMaterialTable()) << endl;
```

4.3. Electromagnetic Field

4.3.1. An Overview of Propagation in a Field

Geant4 is capable of describing and propagating in a variety of fields. Magnetic fields, electric fields and electromagnetic, uniform or non-uniform, can specified for a Geant4 setup. The propagation of tracks inside them can be performed to a user-defined accuracy.

In order to propagate a track inside a field, the equation of motion of the particle in the field is integrated. In general, this is done using a Runge-Kutta method for the integration of ordinary differential equations. However, for specific cases where an analytical solution is known, it is possible to utilize this instead. Several Runge-Kutta methods are available, suitable for different conditions. In specific cases (such as a uniform field where the analytical solution is known) different solvers can also be used. In addition, when an approximate analytical solution is known, it is possible to utilize it in an iterative manner in order to converge to the solution to the precision required. This latter method is currently implemented and can be used particularly well for magnetic fields that are almost uniform.

Once a method is chosen that calculates the track's propagation in a specific field, the curved path is broken up into linear chord segments. These chord segments are determined so that they closely approximate the curved path. The chords are then used to interrogate the Navigator as to whether the track has crossed a volume boundary. Several parameters are available to adjust the accuracy of the integration and the subsequent interrogation of the model geometry.

How closely the set of chords approximates a curved trajectory is governed by a parameter called the *miss distance* (also called the *chord distance*). This is an upper bound for the value of the sagitta - the distance between the 'real' curved trajectory and the approximate linear trajectory of the chord. By setting this parameter, the user can control the precision of the volume interrogation. Every attempt has been made to ensure that all volume interrogations will be made to an accuracy within this *miss distance*.

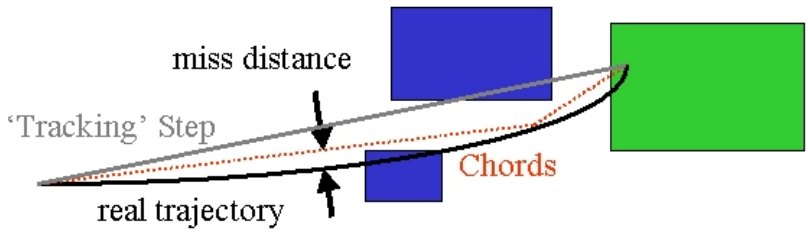


Figure 4.6. The curved trajectory will be approximated by chords, so that the maximum estimated distance between curve and chord is less than the the *miss distance*.

In addition to the *miss distance* there are two more parameters which the user can set in order to adjust the accuracy (and performance) of tracking in a field. In particular these parameters govern the accuracy of the intersection with a volume boundary and the accuracy of the integration of other steps. As such they play an important role for tracking.

The *delta intersection* parameter is the accuracy to which an intersection with a volume boundary is calculated. If a candidate boundary intersection is estimated to have a precision better than this, it is accepted. This parameter is especially important because it is used to limit a bias that our algorithm (for boundary crossing in a field) exhibits. This algorithm calculates the intersection with a volume boundary using a chord between two points on the curved particle trajectory. As such, the intersection point is always on the 'inside' of the curve. By setting a value for this parameter that is much smaller than some acceptable error, the user can limit the effect of this bias on, for example, the future estimation of the reconstructed particle momentum.

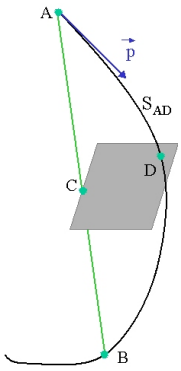


Figure 4.7. The distance between the calculated chord intersection point C and a computed curve point D is used to determine whether C is an accurate representation of the intersection of the curved path ADB with a volume boundary. Here CD is likely too large, and a new intersection on the chord AD will be calculated.

The *delta one step* parameter is the accuracy for the endpoint of 'ordinary' integration steps, those which do not intersect a volume boundary. This parameter is a limit on the estimated error of the endpoint of each physics step. It can be seen as akin to a statistical uncertainty and is not expected to contribute any systematic behavior to physical quantities. In contrast, the bias addressed by *delta intersection* is clearly correlated with potential systematic errors in the momentum of reconstructed tracks. Thus very strict limits on the intersection parameter should be used in tracking detectors or wherever the intersections are used to reconstruct a track's momentum.

Delta intersection and *delta one step* are parameters of the Field Manager; the user can set them according to the demands of his application. Because it is possible to use more than one field manager, different values can be set for different detector regions.

Note that reasonable values for the two parameters are strongly coupled: it does not make sense to request an accuracy of 1 nm for *delta intersection* and accept 100 &#956m for the *delta one step* error value. Nevertheless *delta intersection* is the more important of the two. It is recommended that these parameters should not differ significantly - certainly not by more than an order of magnitude.

4.3.2. Practical Aspects

4.3.2.1. Creating a Magnetic Field for a Detector

The simplest way to define a field for a detector involves the following steps:

1. create a field:

```
G4UniformMagField* magField
  = new G4UniformMagField(G4ThreeVector(0.,0.,fieldValue));
```

2. set it as the default field:

```
G4FieldManager* fieldMgr
  = G4TransportationManager::GetTransportationManager()
    ->GetFieldManager();
   fieldMgr->SetDetectorField(magField);
```

3. create the objects which calculate the trajectory:

```
fieldMgr->CreateChordFinder(magField);
```

To change the accuracy of volume intersection use the `SetDeltaChord` method:

```
```

```
   fieldMgr->GetChordFinder()->SetDeltaChord( G4double newValue);
```

4.3.2.2. Creating a Field for a Part of the Volume Hierarchy

It is possible to create a field for a part of the detector. In particular it can describe the field (with pointer fEmField, for example) inside a logical volume and all its daughters. This can be done by simply creating a `G4FieldManager` and attaching it to a logical volume (with pointer, logicVolumeWithField, for example) or set of logical volumes.

```
 G4bool allLocal = true;
 logicVolumeWithField->SetFieldManager(localFieldManager, allLocal);
```

Using the second parameter to `SetFieldManager` you choose whether daughter volumes of this logical volume will also be given this new field. If it has the value `true`, the field will be assigned also to its daughters, and all their sub-volumes. Else, if it is `false`, it will be copied only to those daughter volumes which do not have a field manager already.

4.3.2.3. Creating an Electric or Electromagnetic Field

The design and implementation of the *Field* category allows and enables the use of an electric or combined electromagnetic field. These fields can also vary with time, as can magnetic fields.

Source listing Example 4.12 shows how to define a uniform electric field for the whole of a detector.

Example 4.12. How to define a uniform electric field for the whole of a detector, extracted from example in examples/extended/field/field02 .

```
// in the header file (or first)
 #include "G4EqMagElectricField.hh"
 #include "G4UniformElectricField.hh"

 ...
   G4ElectricField*        fEMfield;
   G4EqMagElectricField*   fEquation;
   G4MagIntegratorStepper* fStepper;
   G4FieldManager*         fFieldMgr;
   G4double                fMinStep ;
   G4ChordFinder*          fChordFinder ;

// in the source file

 {
   fEMfield = new G4UniformElectricField(
               G4ThreeVector(0.0,100000.0*kilovolt/cm,0.0));

   // Create an equation of motion for this field
   fEquation = new G4EqMagElectricField(fEMfield);

   G4int nvar = 8;
   fStepper = new G4ClassicalRK4( fEquation, nvar );

   // Get the global field manager
   fFieldManager= G4TransportationManager::GetTransportationManager()->
        GetFieldManager();
   // Set this field to the global field manager
   fFieldManager->SetDetectorField(fEMfield );

   fMinStep     = 0.010*mm ; // minimal step of 10 microns

   fIntgrDriver = new G4MagInt_Driver(fMinStep,
                                      fStepper,
                                      fStepper->GetNumberOfVariables() );

   fChordFinder = new G4ChordFinder(fIntgrDriver);
   fFieldManager->SetChordFinder( fChordFinder );

 }
```

An example with an electric field is examples/extended/field/field02, where the class F02ElectricFieldSetup demonstrates how to set these and other parameters, and how to choose different Integration Steppers.

The user can also create their own type of field, inheriting from `G4VField`, and an associated Equation of Motion class (inheriting from `G4EqRhs`) to simulate other types of fields.

4.3.2.4. Choosing a Stepper

Runge-Kutta integration is used to compute the motion of a charged track in a general field. There are many general steppers from which to choose, of low and high order, and specialized steppers for pure magnetic fields. By default, Geant4 uses the classical fourth-order Runge-Kutta stepper, which is general purpose and robust. If the field is known to have specific properties, lower or higher order steppers can be used to obtain the same quality results using fewer computing cycles.

In particular, if the field is calculated from a field map, a lower order stepper is recommended. The less smooth the field is, the lower the order of the stepper that should be used. The choice of lower order steppers includes the third order stepper `G4SimpleHeum`, the second order `G4ImplicitEuler` and `G4SimpleRunge`, and the first order `G4ExplicitEuler`. A first order stepper would be useful only for very rough fields. For somewhat smooth fields (intermediate), the choice between second and third order steppers should be made by trial and error. Trying a few different types of steppers for a particular field or application is suggested if maximum performance is a goal.

The choice of stepper depends on the type of field: magnetic or general. A general field can be an electric or electromagnetic field, it can be a magnetic field or a user-defined field (which requires a user-defined equation of motion.) For a general field several steppers are available as alternatives to the default (`G4ClassicalRK4`):

```
G4int nvar = 8;  // To integrate time & energy
                 //    in addition to position, momentum
G4EqMagElectricField* fEquation= new G4EqMagElectricField(fEMfield);

fStepper = new G4SimpleHeum( fEquation, nvar );
         //  3rd  order, a good alternative to ClassicalRK
fStepper = new G4SimpleRunge( fEquation, nvar );
         //  2nd  order, for less smooth fields
fStepper = new G4CashKarpRKF45( fEquation );
         // 4/5th order for very smooth fields
```

Specialized steppers for pure magnetic fields are also available. They take into account the fact that a local trajectory in a slowly varying field will not vary significantly from a helix. Combining this in with a variation the Runge-Kutta method can provide higher accuracy at lower computational cost when large steps are possible.

```
G4Mag_UsualEqRhs*
   fEquation = new G4Mag_UsualEqRhs(fMagneticField);
fStepper = new G4HelixImplicitEuler( fEquation );
   // Note that for magnetic field that do not vary with time,
   //  the default number of variables suffices.

   // or ..
  fStepper = new G4HelixExplicitEuler( fEquation );
  fStepper = new G4HelixSimpleRunge( fEquation );
```

A new stepper for propagation in magnetic field is available in release 9.3. Choosing the G4NystromRK4 stepper provides accuracy near that of G4ClassicalRK4 (4th order) with a significantly reduced cost in field evaluation. Using a novel analytical expression for estimating the error of a proposed step and the Nystrom reuse of the midpoint field value, it requires only 2 additional field evaluations per attempted step, in place of 10 field evaluations of ClassicalRK4 (which uses the general midpoint method for estimating the step error.)

```
G4Mag_UsualEqRhs*
   pMagFldEquation = new G4Mag_UsualEqRhs(fMagneticField);
fStepper = new G4NystromRK4( pMagFldEquation );
```

It is proposed as an alternative stepper in the case of a pure magnetic field. It is not applicable for the simulation of electric or full electromagnetic or other types of field. For a pure magnetic field, results should be fully compatible with the results of ClassicalRK4 in nearly all cases. (The only potential exceptions are large steps for tracks with small momenta - which cannot be integrated well by any RK method except the Helical extended methods.)

You can choose an alternative stepper either when the field manager is constructed or later. At the construction of the ChordFinder it is an optional argument:

```
G4ChordFinder( G4MagneticField* itsMagField,
               G4double         stepMinimum = 1.0e-2 * mm,
               G4MagIntegratorStepper* pItsStepper = 0 );
```

To change the stepper at a later time use

```
pChordFinder->GetIntegrationDriver()
            ->RenewStepperAndAdjust( newStepper );
```

4.3.2.5. How to Adjust the Accuracy of Propagation

In order to obtain a particular accuracy in tracking particles through an electromagnetic field, it is necessary to adjust the parameters of the field propagation module. In the following section, some of these additional parameters are discussed.

When integration is used to calculate the trajectory, it is necessary to determine an acceptable level of numerical imprecision in order to get performant simulation with acceptable errors. The parameters in Geant4 tell the field module what level of integration inaccuracy is acceptable.

In all quantities which are integrated (position, momentum, energy) there will be errors. Here, however, we focus on the error in two key quantities: the position and the momentum. (The error in the energy will come from the momentum integration).

Three parameters exist which are relevant to the integration accuracy. DeltaOneStep is a distance and is roughly the position error which is acceptable in an integration step. Since many integration steps may be required for a single physics step, DeltaOneStep should be a fraction of the average physics step size. The next two parameters impose a further limit on the relative error of the position/momentum inaccuracy. EpsilonMin and EpsilonMax impose a minimum and maximum on this relative error - and take precedence over DeltaOneStep. (Note: if you set EpsilonMin=EpsilonMax=your-value, then all steps will be made to this relative precision.

Example 4.13. How to set accuracy parameters for the 'global' field of the setup.

```
G4FieldManager *globalFieldManager;

G4TransportationManager *transportMgr=
     G4TransportationManager::GetTransportationManager();

globalFieldManager = transportMgr->GetFieldManager();
                          // Relative accuracy values:
G4double minEps= 1.0e-5;  //   Minimum & value for smallest steps
G4double maxEps= 1.0e-4;  //   Maximum & value for largest steps

globalFieldManager->SetMinimumEpsilonStep( minEps );
globalFieldManager->SetMaximumEpsilonStep( maxEps );
globalFieldManager->SetDeltaOneStep( 0.5e-3 * mm );  // 0.5 micrometer

G4cout << "EpsilonStep: set min= " << minEps << " max= " << maxEps << G4endl;
```

We note that the relevant parameters above limit the inaccuracy in each step. The final inaccuracy due to the full trajectory will accumulate!

The exact point at which a track crosses a boundary is also calculated with finite accuracy. To limit this inaccuracy, a parameter called DeltaIntersection is used. This is a maximum for the inaccuracy of a single boundary crossing.

Thus the accuracy of the position of the track after a number of boundary crossings is directly proportional to the number of boundaries.

4.3.2.6. Reducing the number of field calls to speed-up simulation

An additional method to reduce the number of field evaluations is to utilise the new class G4CachedMagneticField class. It is applicable only for pure magnetic fields which do not vary with time.

```
G4MagneticField * pMagField;  // Your field - Defined elsewhere

G4double                distanceConst = 2.5 * millimeter;
G4MagneticField * pCachedMagField= new G4CachedMagneticField(  pMagField,  distanceConst);
```

4.3.2.7. Choosing different accuracies for the same volume

It is possible to create a FieldManager which has different properties for particles of different momenta (or depending on other parameters of a track). This is useful, for example, in obtaining high accuracy for 'important' tracks (e.g. muons) and accept less accuracy in tracking others (e.g. electrons). To use this, you must create your own field manager which uses the method

```
void ConfigureForTrack( const G4Track * );
```

to configure itself using the parameters of the current track. An example of this will be available in examples/extended/field05.

4.3.2.8. Parameters that must scale with problem size

The default settings of this module are for problems with the physical size of a typical high energy physics setup, that is, distances smaller than about one kilometer. A few parameters are necessary to carry this information to the magnetic field module, and must typically be rescaled for problems of vastly different sizes in order to get reasonable performance and robustness. Two of these parameters are the maximum acceptable step and the minimum step size.

The **maximum acceptable step** should be set to a distance larger than the biggest reasonable step. If the apparatus in a setup has a diameter of two meters, a likely maximum acceptable steplength would be 10 meters. A particle could then take large spiral steps, but would not attempt to take, for example, a 1000-meter-long step in the case of a very low-density material. Similarly, for problems of a planetary scale, such as the earth with its radius of roughly 6400 km, a maximum acceptabe steplength of a few times this value would be reasonable.

An upper limit for the size of a step is a parameter of `G4PropagatorInField`, and can be set by calling its `SetLargestAcceptableStep` method.

The **minimum step size** is used during integration to limit the amount of work in difficult cases. It is possible that strong fields or integration problems can force the integrator to try very small steps; this parameter stops them from becoming unnecessarily small.

Trial steps smaller than this parameter will be treated with less accuracy, and may even be ignored, depending on the situation.

The minimum step size is a parameter of the MagInt_Driver, but can be set in the contstructor of G4ChordFinder, as in the source listing above.

4.3.2.9. Known Issues

Currently it is computationally expensive to change the *miss distance* to very small values, as it causes tracks to be limited to curved sections whose 'bend' is smaller than this value. (The bend is the distance of the mid-point

from the chord between endpoints.) For tracks with small curvature (typically low momentum particles in strong fields) this can cause a large number of steps

- even in areas where there are no volumes to intersect (something that is expected to be addressed in future development, in which the safety will be utilized to partially alleviate this limitation)
- especially in a region near a volume boundary (in which case it is necessary in order to discover whether a track might intersect a volume for only a short distance.)

Requiring such precision at the intersection is clearly expensive, and new development would be necessary to minimize the expense.

By contrast, changing the intersection parameter is less computationally expensive. It causes further calculation for only a fraction of the steps, in particular those that intersect a volume boundary.

4.3.3. Spin Tracking

The effects of a particle's motion on the precession of its spin angular momentum in slowly varying external fields are simulated. The relativistic equation of motion for spin is known as the BMT equation. The equation demonstrates a remarkable property; in a purely magnetic field, in vacuum, and neglecting small anomalous magnetic moments, the particle's spin precesses in such a manner that the longitudinal polarization remains a constant, whatever the motion of the particle. But when the particle interacts with electric fields of the medium and multiple scatters, the spin, which is related to the particle's magnetic moment, does not participate, and the need thus arises to propagate it independent of the momentum vector. In the case of a polarized muon beam, for example, it is important to predict the muon's spin direction at decay-time in order to simulate the decay electron (Michel) distribution correctly.

In order to track the spin of a particle in a magnetic field, you need to code the following:

1. in your DetectorConstruction

```
#include "G4Mag_SpinEqRhs.hh"

  G4Mag_EqRhs* fEquation = new G4Mag_SpinEqRhs(magField);

  G4MagIntegratorStepper* pStepper = new G4ClassicalRK4(fEquation,12);
                                                        notice the 12
```

2. in your PrimaryGenerator

```
  particleGun->SetParticlePolarization(G4ThreeVector p)
```

   for example:

```
  particleGun->
  SetParticlePolarization(-(particleGun->GetParticleMomentumDirection()));

  // or
  particleGun->
  SetParticlePolarization(particleGun->GetParticleMomentumDirection()
                                       .cross(G4ThreeVector(0.,1.,0.)));
```

   where you set the initial spin direction.

While the G4Mag_SpinEqRhs class constructor

```
G4Mag_SpinEqRhs::G4Mag_SpinEqRhs( G4MagneticField* MagField )
   : G4Mag_EqRhs( MagField )
{
```

```
    anomaly = 1.165923e-3;
}
```

sets the muon anomaly by default, the class also comes with the public method:

```
inline void SetAnomaly(G4double a) { anomaly = a; }
```

with which you can set the magnetic anomaly to any value you require.

For the moment, the code is written such that field tracking of the spin is done only for particles with non-zero charge. Please, see the Forum posting: `http://geant4-hn.slac.stanford.edu:5090/HyperNews/public/get/emfields/88/3/1.html` for modifications the user is required to make to facilitate neutron spin tracking.

4.4. Hits

4.4.1. Hit

A hit is a snapshot of the physical interaction of a track in the sensitive region of a detector. In it you can store information associated with a *G4Step* object. This information can be

- the position and time of the step,
- the momentum and energy of the track,
- the energy deposition of the step,
- geometrical information,

or any combination of the above.

G4VHit

G4VHit is an abstract base class which represents a hit. You must inherit this base class and derive your own concrete hit class(es). The member data of your concrete hit class can be, and should be, your choice.

G4VHit has two virtual methods, `Draw()` and `Print()`. To draw or print out your concrete hits, these methods should be implemented. How to define the drawing method is described in Section 8.9.

G4THitsCollection

G4VHit is an abstract class from which you derive your own concrete classes. During the processing of a given event, represented by a *G4Event* object, many objects of the hit class will be produced, collected and associated with the event. Therefore, for each concrete hit class you must also prepare a concrete class derived from *G4VHitsCollection*, an abstract class which represents a vector collection of user defined hits.

G4THitsCollection is a template class derived from *G4VHitsCollection*, and the concrete hit collection class of a particular *G4VHit* concrete class can be instantiated from this template class. Each object of a hit collection must have a unique name for each event.

G4Event has a *G4HCofThisEvent* class object, that is a container class of collections of hits. Hit collections are stored by their pointers, whose type is that of the base class.

An example of a concrete hit class

Example 4.14 shows an example of a concrete hit class.

Example 4.14. An example of a concrete hit class.

```
#ifndef ExN04TrackerHit_h
#define ExN04TrackerHit_h 1

#include "G4VHit.hh"
#include "G4THitsCollection.hh"
#include "G4Allocator.hh"
#include "G4ThreeVector.hh"

class ExN04TrackerHit : public G4VHit
{
  public:

      ExN04TrackerHit();
      ~ExN04TrackerHit();
      ExN04TrackerHit(const ExN04TrackerHit &right);
      const ExN04TrackerHit& operator=(const ExN04TrackerHit &right);
      int operator==(const ExN04TrackerHit &right) const;

      inline void * operator new(size_t);
      inline void operator delete(void *aHit);

      void Draw() const;
      void Print() const;

  private:
      G4double edep;
      G4ThreeVector pos;

  public:
      inline void SetEdep(G4double de)
      { edep = de; }
      inline G4double GetEdep() const
      { return edep; }
      inline void SetPos(G4ThreeVector xyz)
      { pos = xyz; }
      inline G4ThreeVector GetPos() const
      { return pos; }

};

typedef G4THitsCollection<ExN04TrackerHit> ExN04TrackerHitsCollection;

extern G4Allocator<ExN04TrackerHit> ExN04TrackerHitAllocator;

inline void* ExN04TrackerHit::operator new(size_t)
{
  void *aHit;
  aHit = (void *) ExN04TrackerHitAllocator.MallocSingle();
  return aHit;
}

inline void ExN04TrackerHit::operator delete(void *aHit)
{
  ExN04TrackerHitAllocator.FreeSingle((ExN04TrackerHit*) aHit);
}

#endif
```

G4Allocator is a class for fast allocation of objects to the heap through the paging mechanism. For details of *G4Allocator*, refer to Section 3.2.4. Use of *G4Allocator* is not mandatory, but it is recommended, especially for users who are not familiar with the C++ memory allocation mechanism or alternative tools of memory allocation. On the other hand, note that *G4Allocator* is to be used **only** for the concrete class that is **not** used as a base class of any other classes. For example, do **not** use the *G4Trajectory* class as a base class for a customized trajectory class, since *G4Trajectory* uses *G4Allocator*.

G4THitsMap

G4THitsMap is an alternative to *G4THitsCollection*. *G4THitsMap* does not demand *G4VHit*, but instead any variable which can be mapped with an integer key. Typically the key is a copy number of the volume, and the mapped value could for example be a double, such as the energy deposition in a volume. *G4THitsMap* is conve-

nient for applications which do not need to output event-by-event data but instead just accumulate them. All the *G4VPrimitiveScorer* classes discussed in Section 4.4.5 use *G4THitsMap*.

G4THitsMap is derived from the *G4VHitsCollection* abstract base class and all objects of this class are also stored in *G4HCofThisEvent* at the end of an event. How to access a *G4THitsMap* object is discussed in the following section (Section 4.4.5).

4.4.2. Sensitive detector

G4VSensitiveDetector

G4VSensitiveDetector is an abstract base class which represents a detector. The principal mandate of a sensitive detector is the construction of hit objects using information from steps along a particle track. The `ProcessHits()` method of *G4VSensitiveDetector* performs this task using *G4Step* objects as input. In the case of a "Readout" geometry (see Section 4.4.3), objects of the *G4TouchableHistory* class may be used as an optional input.

Your concrete detector class should be instantiated with the unique name of your detector. The name can be associated with one or more global names with "/" as a delimiter for categorizing your detectors. For example

```
    myEMcal = new MyEMcal("/myDet/myCal/myEMcal");
```

where `myEMcal` is the name of your detector. The pointer to your sensitive detector must be set to one or more *G4LogicalVolume* objects to set the sensitivity of these volumes. The pointer should also be registered to *G4SDManager*, as described in Section 4.4.4.

G4VSensitiveDetector has three major virtual methods.

`ProcessHits()`
: This method is invoked by *G4SteppingManager* when a step is composed in the *G4LogicalVolume* which has the pointer to this sensitive detector. The first argument of this method is a *G4Step* object of the current step. The second argument is a *G4TouchableHistory* object for the ``Readout geometry'' described in the next section. The second argument is `NULL` if ``Readout geometry'' is not assigned to this sensitive detector. In this method, one or more *G4VHit* objects should be constructed if the current step is meaningful for your detector.

`Initialize()`
: This method is invoked at the beginning of each event. The argument of this method is an object of the *G4HCofThisEvent* class. Hit collections, where hits produced in this particular event are stored, can be associated with the *G4HCofThisEvent* object in this method. The hit collections associated with the *G4HCofThisEvent* object during this method can be used for ``during the event processing'' digitization.

`EndOfEvent()`
: This method is invoked at the end of each event. The argument of this method is the same object as the previous method. Hit collections occasionally created in your sensitive detector can be associated with the *G4HCofThisEvent* object.

4.4.3. Readout geometry

This section describes how a ``Readout geometry'' can be defined. A Readout geometry is a virtual, parallel geometry for obtaining the channel number.

As an example, the accordion calorimeter of **ATLAS** has a complicated tracking geometry, however the readout can be done by simple cylindrical sectors divided by theta, phi, and depth. Tracks will be traced in the tracking geometry, the ``real'' one, and the sensitive detector will have its own readout geometry Geant4 will message to find to which ``readout'' cell the current hit belongs.

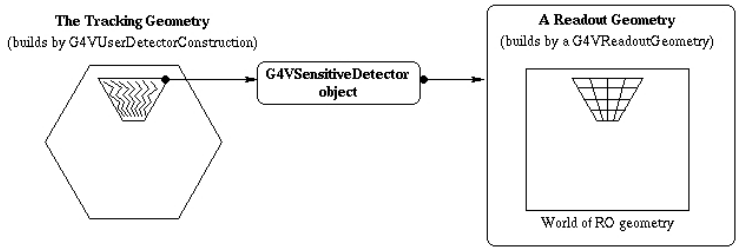


Figure 4.8. Association of tracking and readout geometry.

Figure 4.8 shows how this association is done in Geant4. The first step is to associate a sensitive detector to a volume of the tracking geometry, in the usual way (see Section 4.4.2). The next step is to associate your *G4VReadoutGeometry* object to the sensitive detector.

At tracking time, the base class *G4VReadoutGeometry* will provide to your sensitive detector code the *G4TouchableHistory* in the Readout geometry at the beginning of the step position (position of *PreStepPoint* of *G4Step*) and at this position only.

This *G4TouchableHistory* is given to your sensitive detector code through the *G4VSensitiveDetector* virtual method:

```
G4bool processHits(G4Step* aStep, G4TouchableHistory* ROhist);
```

by the `ROhist` argument.

Thus, you will be able to use information from both the *G4Step* and the *G4TouchableHistory* coming from your Readout geometry. Note that since the association is done through a sensitive detector object, it is perfectly possible to have several Readout geometries in parallel.

Definition of a virtual geometry setup

The base class for the implementation of a Readout geometry is *G4VReadoutGeometry*. This class has a single pure virtual protected method:

```
virtual G4VPhysicalVolume* build() = 0;
```

which you must override in your concrete class. The *G4VPhysicalVolume* pointer you will have to return is of the physical world of the Readout geometry.

The step by step procedure for constructing a Readout geometry is:

- inherit from *G4VReadoutGeometry* to define a *MyROGeom* class;
- implement the Readout geometry in the `build()` method, returning the physical world of this geometry.

  The world is specified in the same way as for the detector construction: a physical volume with no mother. The axis system of this world is the same as the one of the world for tracking.

  In this geometry you need to declare the sensitive parts in the same way as in the tracking geometry: by setting a non-`NULL` *G4VSensitiveDetector* pointer in, say, the relevant *G4LogicalVolume* objects. This sensitive class needs to be there, but will not be used.

  You will also need to assign well defined materials to the volumes you place in this geometry, but these materials are irrelevant since they will not be seen by the tracking. It is foreseen to allow the setting of a `NULL` pointer in this case of the parallel geometry.

- in the `construct()` method of your concrete *G4VUserDetectorConstruction* class:
  - instantiate your Readout geometry:

```
MyROGeom* ROgeom = new MyROGeom("ROName");
```

  - build it:

```
ROgeom->buildROGeometry();
```

    That will invoke your `build()` method.
  - Instantiate the sensitive detector which will receive the `ROGeom` pointer, `MySensitive`, and add this sensitive to the *G4SDManager*. Associate this sensitive to the volume(s) of the tracking geometry as usual.
  - Associate the sensitive to the Readout geometry:

```
MySensitive->SetROgeometry(ROgeom);
```

4.4.4. G4SDManager

G4SDManager is the singleton manager class for sensitive detectors.

Activation/inactivation of sensitive detectors

The user interface commands `activate` and `inactivate` are available to control your sensitive detectors. For example:

```
/hits/activate detector_name
/hits/inactivate detector_name
```

where `detector_name` can be the detector name or the category name.

For example, if your EM calorimeter is named

```
/myDet/myCal/myEMcal
/hits/inactivate myCal
```

will inactivate all detectors belonging to the `myCal` category.

Access to the hit collections

Hit collections are accessed for various cases.

- Digitization
- Event filtering in *G4VUserStackingAction*
- ``End of event'' simple analysis
- Drawing / printing hits

The following is an example of how to access the hit collection of a particular concrete type:

```
G4SDManager* fSDM = G4SDManager::GetSDMpointer();
G4RunManager* fRM = G4RunManager::GetRunManager();
```

```
G4int collectionID = fSDM->GetCollectionID("collection_name");
const G4Event* currentEvent = fRM->GetCurrentEvent();
G4HCofThisEvent* HCofEvent = currentEvent->GetHCofThisEvent();
MyHitsCollection* myCollection = (MyHitsCollection*)(HC0fEvent->GetHC(collectionID));
```

4.4.5. *G4MultiFunctionalDetector* and *G4VPrimitiveScorer*

G4MultiFunctionalDetector is a concrete class derived from *G4VSensitiveDetector*. Instead of implementing a user-specific detector class, *G4MultiFunctionalDetector* allows the user to register *G4VPrimitiveScorer* classes to build up the sensitivity. *G4MultiFunctionalDetector* should be instantiated in the users detector construction with its unique name and should be assigned to one or more *G4LogicalVolume*s.

G4VPrimitiveScorer is an abstract base class representing a class to be registered to *G4MultiFunctionalDetector* that creates a *G4THitsMap* object of one physics quantity for an event. Geant4 provides many concrete primitive scorer classes listed in Section 4.4.6, and the user can also implement his/her own primitive scorers. Each primitive scorer object must be instantiated with a name that must be unique among primitive scorers registered in a *G4MultiFunctionalDetector*. Please note that a primitive scorer object must **not** be shared by more than one *G4MultiFunctionalDetector* object.

As mentioned in Section 4.4.1, each *G4VPrimitiveScorer* generates one *G4THitsMap* object per event. The name of the map object is the same as the name of the primitive scorer. Each of the concrete primitive scorers listed in Section 4.4.6 generates a *G4THitsMap<G4double>* that maps a *G4double* value to its key integer number. By default, the key is taken as the copy number of the *G4LogicalVolume* to which *G4MultiFunctionalDetector* is assigned. In case the logical volume is uniquely placed in its mother volume and the mother is replicated, the copy number of its mother volume can be taken by setting the second argument of the *G4VPrimitiveScorer* constructor, "*depth*" to 1, i.e. one level up. Furthermore, in case the key must consider more than one copy number of a different geometry hierarchy, the user can derive his/her own primitive scorer from the provided concrete class and implement the *GetIndex(G4Step*)* virtual method to return the unique key.

Example 4.15 shows an example of primitive sensitivity class definitions.

Example 4.15. An example of defining primitive sensitivity classes taken from *ExN07DetectorConstruction*.

```
void ExN07DetectorConstruction::SetupDetectors()
{
  G4String filterName, particleName;

  G4SDParticleFilter* gammaFilter =
    new G4SDParticleFilter(filterName="gammaFilter",particleName="gamma");
  G4SDParticleFilter* electronFilter =
    new G4SDParticleFilter(filterName="electronFilter",particleName="e-");
  G4SDParticleFilter* positronFilter =
    new G4SDParticleFilter(filterName="positronFilter",particleName="e+");
  G4SDParticleFilter* epFilter = new G4SDParticleFilter(filterName="epFilter");
  epFilter->add(particleName="e-");
  epFilter->add(particleName="e+");


  for(G4int i=0;i<3;i++)
  {
   for(G4int j=0;j<2;j++)
   {
    // Loop counter j = 0 : absorber
    //               = 1 : gap
    G4String detName = calName[i];
    if(j==0)
    { detName += "_abs"; }
    else
    { detName += "_gap"; }
    G4MultiFunctionalDetector* det = new G4MultiFunctionalDetector(detName);

    //  The second argument in each primitive means the "level" of geometrical hierarchy,
    // the copy number of that level is used as the key of the G4THitsMap.
    //  For absorber (j = 0), the copy number of its own physical volume is used.
    //  For gap (j = 1), the copy number of its mother physical volume is used, since there
    // is only one physical volume of gap is placed with respect to its mother.
    G4VPrimitiveScorer* primitive;
    primitive = new G4PSEnergyDeposit("eDep",j);
    det->RegisterPrimitive(primitive);
    primitive = new G4PSNofSecondary("nGamma",j);
    primitive->SetFilter(gammaFilter);
    det->RegisterPrimitive(primitive);
    primitive = new G4PSNofSecondary("nElectron",j);
    primitive->SetFilter(electronFilter);
    det->RegisterPrimitive(primitive);
    primitive = new G4PSNofSecondary("nPositron",j);
    primitive->SetFilter(positronFilter);
    det->RegisterPrimitive(primitive);
    primitive = new G4PSMinKinEAtGeneration("minEkinGamma",j);
    primitive->SetFilter(gammaFilter);
    det->RegisterPrimitive(primitive);
    primitive = new G4PSMinKinEAtGeneration("minEkinElectron",j);
    primitive->SetFilter(electronFilter);
    det->RegisterPrimitive(primitive);
    primitive = new G4PSMinKinEAtGeneration("minEkinPositron",j);
    primitive->SetFilter(positronFilter);
    det->RegisterPrimitive(primitive);
    primitive = new G4PSTrackLength("trackLength",j);
    primitive->SetFilter(epFilter);
    det->RegisterPrimitive(primitive);
    primitive = new G4PSNofStep("nStep",j);
    primitive->SetFilter(epFilter);
    det->RegisterPrimitive(primitive);

    G4SDManager::GetSDMpointer()->AddNewDetector(det);
    if(j==0)
    { layerLogical[i]->SetSensitiveDetector(det); }
    else
    { gapLogical[i]->SetSensitiveDetector(det); }
   }
  }
}
```

Each *G4THitsMap* object can be accessed from *G4HCofThisEvent* with a unique collection ID number. This ID number can be obtained from *G4SDManager::GetCollectionID()* with a name of *G4MultiFunctionalDetector*

and *G4VPrimitiveScorer* connected with a slush ("/"). *G4THitsMap* has a [] operator taking the key value as an argument and returning **the pointer** of the value. Please note that the [] operator returns **the pointer** of the value. If you get zero from the [] operator, it does **not** mean the value is zero, but that the provided key does not exist. The value itself is accessible with an astarisk ("*"). It is advised to check the validity of the returned pointer before accessing the value. *G4THitsMap* also has a += operator in order to accumulate event data into run data. Example 4.16 shows the use of *G4THitsMap*.

Example 4.16. An example of accessing to *G4THitsMap* objects.

```
#include "ExN07Run.hh"
#include "G4Event.hh"
#include "G4HCofThisEvent.hh"
#include "G4SDManager.hh"

ExN07Run::ExN07Run()
{
  G4String detName[6] = {"Calor-A_abs","Calor-A_gap","Calor-B_abs","Calor-B_gap",
                         "Calor-C_abs","Calor-C_gap"};
  G4String primNameSum[6] = {"eDep","nGamma","nElectron","nPositron","trackLength","nStep"};
  G4String primNameMin[3] = {"minEkinGamma","minEkinElectron","minEkinPositron"};

  G4SDManager* SDMan = G4SDManager::GetSDMpointer();
  G4String fullName;
  for(size_t i=0;i<6;i++)
  {
    for(size_t j=0;j<6;j++)
    {
      fullName = detName[i]+"/"+primNameSum[j];
      colIDSum[i][j] = SDMan->GetCollectionID(fullName);
    }
    for(size_t k=0;k<3;k++)
    {
      fullName = detName[i]+"/"+primNameMin[k];
      colIDMin[i][k] = SDMan->GetCollectionID(fullName);
    }
  }
}


void ExN07Run::RecordEvent(const G4Event* evt)
{
  G4HCofThisEvent* HCE = evt->GetHCofThisEvent();
  if(!HCE) return;
  numberOfEvent++;
  for(size_t i=0;i<6;i++)
  {
    for(size_t j=0;j<6;j++)
    {
      G4THitsMap<G4double>* evtMap = (G4THitsMap<G4double>*)(HCE->GetHC(colIDSum[i][j]));
      mapSum[i][j] += *evtMap;
    }
    for(size_t k=0;k<3;k++)
    {
      G4THitsMap<G4double>* evtMap = (G4THitsMap<G4double>*)(HCE->GetHC(colIDMin[i][k]));
      std::map<G4int,G4double*>::iterator itr = evtMap->GetMap()->begin();
      for(; itr != evtMap->GetMap()->end(); itr++)
      {
        G4int key = (itr->first);
        G4double val = *(itr->second);
        G4double* mapP = mapMin[i][k][key];
        if( mapP && (val>*mapP) ) continue;
        mapMin[i][k].set(key,val);
      }
    }
  }
}
```

4.4.6. Concrete classes of *G4VPrimitiveScorer*

With Geant4 version 8.0, several concrete primitive scorer classes are provided, all of which are derived from the *G4VPrimitiveScorer* abstract base class and which are to be registered to *G4MultiFunctionalDetector*. Each of them contains one *G4THitsMap* object and scores a simple double value for each key.

Track length scorers

G4PSTrackLength
: The track length is defined as the sum of step lengths of the particles inside the cell. Bt default, the track weight is not taken into account, but could be used as a multiplier of each step length if the *Weighted()* method of this class object is invoked.

G4PSPassageTrackLength
: The passage track length is the same as the track length in *G4PSTrackLength*, except that only tracks which pass through the volume are taken into account. It means newly-generated or stopped tracks inside the cell are excluded from the calculation. By default, the track weight is not taken into account, but could be used as a multiplier of each step length if the *Weighted()* method of this class object is invoked.

Deposited energy scorers

G4PSEnergyDeposit
: This scorer stores a sum of particles' energy deposits at each step in the cell. The particle weight is multiplied at each step.

G4PSDoseDeposit
: In some cases, dose is a more convenient way to evaluate the effect of energy deposit in a cell than simple deposited energy. The dose deposit is defined by the sum of energy deposits at each step in a cell divided by the mass of the cell. The mass is calculated from the density and volume of the cell taken from the methods of *G4VSolid* and *G4LogicalVolume*. The particle weight is multiplied at each step.

Current and flux scorers

There are two different definitions of a particle's flow for a given geometry. One is a current and the other is a flux. In our scorers, the current is simply defined as the number of particles (with the particle's weight) at a certain surface or volume, while the flux takes the particle's injection angle to the geometry into account. The current and flux are usually defined at a surface, but volume current and volume flux are also provided.

G4PSFlatSurfaceCurrent
: Flat surface current is a surface based scorer. The present implementation is limited to scoring only at the -Z surface of a *G4Box* solid. The quantity is defined by the number of tracks that reach the surface. The user must choose a direction of the particle to be scored. The choices are fCurrent_In, fCurrent_Out, or fCurrent_InOut, one of which must be entered as the second argument of the constructor. Here, fCurrent_In scores incoming particles to the cell, while fCurrent_Out scores only outgoing particles from the cell. fCurrent_InOut scores both directions. The current is multiplied by particle weight and is normalized for a unit area.

G4PSSphereSurfaceCurrent
: Sphere surface current is a surface based scorer, and similar to the G4PSFlatSurfaceCurrent. The only difference is that the surface is defined at the **inner surface** of a G4Sphere solid.

G4PSPassageCurrent
: Passage current is a volume-based scorer. The current is defined by the number of tracks that pass through the volume. A particle weight is applied at the exit point. A passage current is defined for a volume.

G4PSFlatSurfaceFlux
: Flat surface flux is a surface based flux scorer. The surface flux is defined by the number of tracks that reach the surface. The expression of surface flux is given by the sum of W/cos(t)/A, where W, t and A represent particle weight, injection angle of particle with respect to the surface normal, and area of the surface. The user must enter one of the particle directions, fFlux_In, fFlux_Out, or fFlux_InOut in the constructor. Here, fFlux_In scores incoming particles to the cell, while fFlux_Out scores outgoing particles from the cell. fFlux_InOut scores both directions.

G4PSCellFlux
: Cell flux is a volume based flux scorer. The cell flux is defined by a track length (L) of the particle inside a volume divided by the volume (V) of this cell. The track length is calculated by a sum of the step lengths

in the cell. The expression for cell flux is given by the sum of (W*L)/V, where W is a particle weight, and is multiplied by the track length at each step.

G4PSPassageCellFlux
: Passage cell flux is a volume based scorer similar to *G4PSCellFlux*. The only difference is that tracks which pass through a cell are taken into account. It means generated or stopped tracks inside the volume are excluded from the calculation.

Other scorers

G4PSMinKinEAtGeneration
: This scorer records the minimum kinetic energy of secondary particles at their production point in the volume in an event. This primitive scorer does not integrate the quantity, but records the minimum quantity.

G4PSNofSecondary
: This class scores the number of secondary particles generated in the volume. The weight of the secondary track is taken into account.

G4PSNofStep
: This class scores the number of steps in the cell. A particle weight is not applied.

G4PSCellCharge
: This class scored the total charge of particles which has stoped in the volume.

4.4.7. *G4VSDFilter* and its derived classes

G4VSDFilter is an abstract class that represents a track filter to be associated with *G4VSensitiveDetector* or *G4VPrimitiveScorer*. It defines a virtual method

```
G4bool Accept(const G4Step*)
```

that should return *true* if this particular step should be scored by the *G4VSensitiveDetector* or *G4VPrimitiveScorer*.

While the user can implement his/her own filter class, Geant4 version 8.0 provides the following concrete filter classes:

G4SDChargedFilter
: All charged particles are accepted.

G4SDNeutralFilter
: All neutral particles are accepted.

G4SDParticleFilter
: Particle species which are registered to this filter object by *Add("particle_name")* are accepted. More than one species can be registered.

G4SDKineticEnergyFilter
: A track with kinetic energy greater than or equal to EKmin and smaller than EKmin is accepted. EKmin and EKmax should be defined as arguments of the constructor. The default values of EKmin and EKmax are zero and DBL_MAX.

G4SDParticleWithEnergyFilter
: Combination of *G4SDParticleFilter* and *G4SDParticleWithEnergyFilter*.

The use of the *G4SDParticleFilter* class is demonstrated in Example 4.15, where filters which accept gamma, electron, positron and electron/positron are defined.

4.4.8. Scoring for Event Biasing

Scoring for Event Biasing (described in Section 3.7) is a very specific use case whereby particle weights and fluxes through importance cells are required. The goals of the scoring technique are to:

- appraise particle quantities related to special regions or surfaces,
- be applicable to all "cells" (physical volumes or replicas) of a given geometry,
- be customizable.

Standard scoring must be provided for quantities such as tracks entering a cell, average weight of entering tracks, energy of entering tracks, and collisions inside the cell.

A number of scorers have been created for this specific appliction:

G4PSNofCollision
: This scorer records the number of collisions that occur within a scored volume/cell. There is the additional possibility to take into account the track weight whilst scoring the number of collisions, via the following command:

```
G4PSNofCollision*   scorer1 = new G4PSNofCollision(psName="CollWeight");
scorer1->Weighted(true);
```

G4PSPopulation
: This scores the number of tracks within in a given cell per event.

G4PSTrackLength
: The track lengths within a cell are measured and if, additionally, the result is desired to be weighted then the following code has to be implemented:

```
G4PSTrackLength* scorer5 = new G4PSTrackLength(psName="SLW");
scorer5->Weighted(true);
```

Further if the energy track flux is required then the following should be implemented:

```
G4PSTrackLength* scorer6 = new G4PSTrackLength(psName="SLWE");
scorer6->Weighted(true);
scorer6->MultiplyKineticEnergy(true);
MFDet->RegisterPrimitive(scorer6);
```

Alternatively to measure the flux per unit velocity then:

```
G4PSTrackLength* scorer7 = new G4PSTrackLength(psName="SLW_V");
scorer7->Weighted(true);
scorer7->DivideByVelocity(true);
MFDet->RegisterPrimitive(scorer7);
```

Finally to measure the flux energy per unit velocity then:

```
G4PSTrackLength* scorer8 = new G4PSTrackLength(psName="SLWE_V");
scorer8->Weighted(true);
scorer8->MultiplyKineticEnergy(true);
scorer8->DivideByVelocity(true);
MFDet->RegisterPrimitive(scorer8);
```

4.5. Digitization

4.5.1. Digi

A hit is created by a sensitive detector when a step goes through it. Thus, the sensitive detector is associated to the corresponding *G4LogicalVolume* object(s). On the other hand, a digit is created using information of hits and/or other digits by a digitizer module. The digitizer module is not associated with any volume, and you have to implicitly invoke the `Digitize()` method of your concrete *G4VDigitizerModule* class.

Typical usages of digitizer module include:

- simulate ADC and/or TDC

- simulate readout scheme
- generate raw data
- simulate trigger logics
- simulate pile up

G4VDigi

G4VDigi is an abstract base class which represents a digit. You have to inherit this base class and derive your own concrete digit class(es). The member data of your concrete digit class should be defined by yourself. *G4VDigi* has two virtual methods, `Draw()` and `Print()`.

G4TDigiCollection

G4TDigiCollection is a template class for digits collections, which is derived from the abstract base class *G4VDigiCollection*. *G4Event* has a *G4DCofThisEvent* object, which is a container class of collections of digits. The usages of *G4VDigi* and *G4TDigiCollection* are almost the same as *G4VHit* and *G4THitsCollection*, respectively, explained in the previous section.

4.5.2. Digitizer module

G4VDigitizerModule

G4VDigitizerModule is an abstract base class which represents a digitizer module. It has a pure virtual method, `Digitize()`. A concrete digitizer module must have an implementation of this virtual method. The Geant4 kernel classes do not have a ``built-in" invocation to the `Digitize()` method. You have to implement your code to invoke this method of your digitizer module.

In the `Digitize()` method, you construct your *G4VDigi* concrete class objects and store them to your *G4TDigiCollection* concrete class object(s). Your collection(s) should be associated with the *G4DCofThisEvent* object.

G4DigiManager

G4DigiManager is the singleton manager class of the digitizer modules. All of your concrete digitizer modules should be registered to *G4DigiManager* with their unique names.

```
G4DigiManager * fDM = G4DigiManager::GetDMpointer();
MyDigitizer * myDM = new MyDigitizer( "/myDet/myCal/myEMdigiMod" );
fDM->AddNewModule(myDM);
```

Your concrete digitizer module can be accessed from your code using the unique module name.

```
G4DigiManager * fDM = G4DigiManager::GetDMpointer();
MyDigitizer * myDM = fDM->FindDigitizerModule( "/myDet/myCal/myEMdigiMod" );
myDM->Digitize();
```

Also, *G4DigiManager* has a *Digitize()* method which takes the unique module name.

```
G4DigiManager * fDM = G4DigiManager::GetDMpointer();
MyDigitizer * myDM = fDM->Digitize( "/myDet/myCal/myEMdigiMod" );
```

How to get hitsCollection and/or digiCollection

G4DigiManager has the following methods to access to the hits or digi collections of the currently processing event or of previous events.

First, you have to get the collection ID number of the hits or digits collection.

```
G4DigiManager * fDM = G4DigiManager::GetDMpointer();
G4int myHitsCollID = fDM->GetHitsCollectionID( "hits_collection_name" );
```

```
    G4int myDigiCollID = fDM->GetDigiCollectionID( "digi_collection_name" );
```

Then, you can get the pointer to your concrete *G4THitsCollection* object or *G4TDigiCollection* object of the currently processing event.

```
    MyHitsCollection * HC = fDM->GetHitsCollection( myHitsCollID );
    MyDigiCollection * DC = fDM->GetDigiCollection( myDigiCollID );
```

In case you want to access to the hits or digits collection of previous events, add the second argument.

```
    MyHitsCollection * HC = fDM->GetHitsCollection( myHitsCollID, n );
    MyDigiCollection * DC = fDM->GetDigiCollection( myDigiCollID, n );
```

where, `n` indicates the hits or digits collection of the n^{th} previous event.

4.6. Object Persistency

4.6.1. Persistency in Geant4

Object persistency is provided by Geant4 as an optional category, so that the user may run Geant4 with or without an object database management system (ODBMS).

When a usual (transient) object is created in C++, the object is placed onto the application heap and it ceases to exist when the application terminates. Persistent objects, on the other hand, live beyond the termination of the application process and may then be accessed by other processes (in some cases, by processes on other machines).

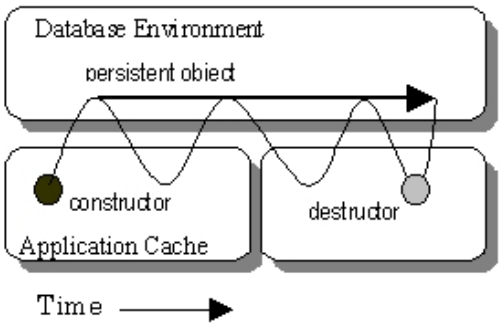


Figure 4.9. Persistent object.

C++ does not have, as an intrinsic part of the language, the ability to store and retrieve persistent objects. Geant4 provides an abstract framework for persistency of hits, digits and events.

Two examples demonstrating an implementation of object persistency using one of the tools accessible through the available interface, is provided in `examples/extended/persistency`.

4.6.2. Using Reflex for persistency of Geant4 objects

Object persistency of Geant4 objects is also possible by the mean of the Reflex library. Reflex provides, in a non-intrusive way, reflection capabilities to C++ classes by generating "dictionary information" for them. Those dictionaries can then be loaded in memory allowing direct persistency of the given objects without any instrumentation of the code. The Reflex library is also part of ROOT (since release `v5.08`).

The basic steps that one needs to do in order to use Reflex with ROOT I/O for arbitrary C++ classes is:

1. Generate the dictionary for the given classes using the `genreflex` tool from ROOT (this usually is done by adding the appropriate command to the makefile)
2. Add initialization of ROOT I/O and loading of the generated dictionary for the given classes in the appropriate part of the code

3. Whenever the objects to be persistified are available, call the `WriteObject` method of `TFile` with the pointer to the appropriate object as argument (usually it is some sort of container, like `std::vector` containing the collection of objects to be persistified)

The two examples (`P01` and `P02`) provided in `examples/extended/persistency` demonstrate how to perform object persistency using the Reflex mechanism in ROOT I/O for storing hits and geometry description.

4.7. Parallel Geometries

4.7.1. A parallel world

Occasionally, it is not straightforward to define geometries for sensitive detectors, importance geometries or envelopes for shower parameterization to be coherently assigned to volumes in the tracking (mass) geometry. The parallel navigation functionality introduced since release 8.2 of Geant4, allows the user to define more than one worlds simultaneously. The `G4Transportation` process will see all worlds simultaneously; steps will be limited by both boundaries of the mass and parallel geometries.

In a parallel world, the user can define volumes in arbitrary manner with sensitivity, regions, shower parameterization setups, and/or importance weight for biasing. Volumes in different worlds can overlap.

Here are restrictions to be considered for the parallel geometry:

- Materials, production thresholds and EM field are used only from the mass geometry. Even if such *physical* quantities are defined in a parallel world, they do not affect to the simulation.
- Although all worlds will be comprehensively taken care by the `G4Transportation` process for the navigation, each parallel world must have its own process assigned to achieve its purpose. For example: in case the user defines a sensitive detector to a parallel world, a process dedicated to the parallel world is responsible to invoke this detector. The `G4SteppingManager` treats only the detectors in the mass geometry. For this case of detector sensitivity defined in a parallel world, a `G4ParallelWorldScoringProcess` process must be defined in the physics list (see Section 4.7.3).

4.7.2. Defining a parallel world

A parallel world should be defined in the `Construct()` virtual method of the user's class derived from the abstract base class *G4VUserParallelWorld*.

Example 4.17. An example header file of a concrete user parallel world class.

```
#ifndef MyParallelWorld_h
#define MyParallelWorld_h 1

#include "globals.hh"
#include "G4VUserParallelWorld.hh"

class MyParallelWorld : public G4VUserParallelWorld
{
  public:
    MyParallelWorld(G4String worldName);
    virtual ~MyParallelWorld();

  public:
    virtual void Construct();
};

#endif
```

A parallel world must have its unique name, which should be set to the `G4VUserParallelWorld` base class as an argument of the base class constructor.

The world physical volume of the parallel world is provided by the `G4RunManager` as a clone of the mass geometry. In the `Construct()` virtual method of the user's class, the pointer to this cloned world physical volume is available through the `GetWorld()` method defined in the base class. The user should fill the volumes

in the parallel world by using this provided world volume. For a logical volume in a parallel world, the material pointer can be `0`. Even if specified a valid material pointer, it will not be taken into account by any physics process.

Example 4.18. An example source code of a concrete user parallel world class.

```
#include "MyParallelWorld.hh"
#include "G4LogicalVolume.hh"
#include "G4VPhysicalVolume.hh"
#include "G4Box.hh"
#include "G4PVPlacement.hh"

MyParallelWorld::MyParallelWorld(G4String worldName)
:G4VUserParallelWorld(worldName)
{;}

MyParallelWorld::~MyParallelWorld()
{;}

void MyParallelWorld::Construct()
{
  G4VPhysicalVolume* ghostWorld = GetWorld();
  G4LogicalVolume* worldLogical = ghostWorld->GetLogicalVolume();

  // place volumes in the parallel world here. For example ...
  //
  G4Box * ghostSolid = new G4Box("GhostdBox", 60.*cm, 60.*cm, 60.*cm);
  G4LogicalVolume * ghostLogical
        = new G4LogicalVolume(ghostSolid, 0, "GhostLogical", 0, 0, 0);
  new G4PVPlacement(0, G4ThreeVector(), ghostLogical,
                    "GhostPhysical", worldLogical, 0, 0);
}
```

In case the user needs to define more than one parallel worlds, each of them must be implemented through its dedicated class. Each parallel world should be registered to the mass geometry class using the method `RegisterParallelWorld()` available through the class `G4VUserDetectorConstruction`. The registration must be done -before- the mass world is registed to the `G4RunManager`.

Example 4.19. Typical implementation in the `main()` to define a parallel world.

```
  // RunManager construction
  //
  G4RunManager* runManager = new G4RunManager;

  // mass world
  //
  MyDetectorConstruction* massWorld = new MyDetectorConstruction;

  // parallel world
  //
  massWorld->RegisterParallelWorld(new MyParallelWorld("ParallelScoringWorld"));

  // set mass world to run manager
  //
  runManager->SetUserInitialization(massWorld);
```

4.7.3. Detector sensitivity in a parallel world

Any kind of `G4VSensitiveDetector` object can be defined in volumes in a parallel world, exactly at the same manner for the mass geometry. Once the user defines the sensitive detector in a parallel world, he/she must define a process which takes care of these detectors.

The `G4ParallelWorldScoringProcess` is the class provided for this purpose. This process must be defined to all kinds of particles which need to be "detected". This process must be ordered *just after `G4Transporation` and prior to any other physics processes*. The name of the parallel world where the `G4ParallelWorldScoringProcess` is responsible for, must be defined through the method `SetParallelWorld()` available from the class `G4ParallelWorldScoringProcess`. If the user has more than one parallel worlds with detectors, for each of the parallel worlds, dedicated

`G4ParallelWorldScoringProcess` objects must be instantiated with the name of each parallel world respectively and registered to the particles.

Example 4.20. Define `G4ParallelWorldScoringProcess`.

```
  // Add parallel world scoring process
  //
  G4ParallelWorldScoringProcess* theParallelWorldScoringProcess
      = new G4ParallelWorldScoringProcess("ParaWorldScoringProc");
  theParallelWorldScoringProcess->SetParallelWorld("ParallelScoringWorld");

  theParticleIterator->reset();
  while( (*theParticleIterator)() )
  {
    G4ParticleDefinition* particle = theParticleIterator->value();
    if (!particle->IsShortLived())
    {
      G4ProcessManager* pmanager = particle->GetProcessManager();
      pmanager->AddProcess(theParallelWorldScoringProcess);
      pmanager->SetProcessOrderingToLast(theParallelWorldScoringProcess, idxAtRest);
      pmanager->SetProcessOrdering(theParallelWorldScoringProcess, idxAlongStep, 1);
      pmanager->SetProcessOrderingToLast(theParallelWorldScoringProcess, idxPostStep);
    }
  }
```

At the end of processing an event, all hits collections made for the parallel world are stored in `G4HCofThisEvent` as well as those for the mass geometry.

4.8. Command-based scoring

Command-based scoring in Geant4 utilizes parallel navigation in a parallel world volume as descibed in the previous sections. Through interactive commands, the user can define :

- A parallel world for scoring and three-dimensional mesh in it
- Arbitrary number of physics quantities to be scored and filters

After scoring (i.e. a run), the user can visualize the score and dump scores into a file. All available UI commands are listed in List of built-in commands.

Command-based scoring is an optional functionality and the user has to explicity define its use in the `main()`. To do this, the method `G4ScoringManager::GetScoringManager()` must be invoked *right after* the instantiation of `G4RunManager`.

Example 4.21. A user `main()` to use the command-based scoring

```
#include "G4RunManager.hh"
#include "G4ScoringManager.hh"

int main(int argc,char** argv)
{
 // Construct the run manager
 G4RunManager * runManager = new G4RunManager;

 // Activate command-based scorer
 G4ScoringManager::GetScoringManager();

 ...

}
```

4.8.2. Defining a scoring mesh

To define a scoring mesh, the user has to specify the followings.

- Shape and name of the 3D scoring mesh. Currently, box is the only available shape.

- Size of the scoring mesh. Mesh size must be specified as "half width" similar to the arguments of `G4Box`.
- Number of bins for each axes. Note that too hugh number causes immense memory consumption.
- Optionally, position and rotation of the mesh. If not specified, the mesh is positioned at the center of the world volume without rotation.

For a scoring mesh the user can have arbitrary number of quantities to be scored for each cell of the mesh. For each scoring quantity, the use can set one filter. Please note that `/score/filter` affects on the preceding scorer. Names of scorers and filters must be unique for the mesh. It is possible to define more than one scorer of same kind with different names and, likely, with different filters.

Defining a scoring mesh and scores in the mesh should terminate with the `/score/close` command. The following sample UI commands define a scoring mesh named `boxMesh_1`, size of which is 2 m * 2 m * 2 m, and sliced into 30 cells along each axes. For each cell energy deposition, number of steps of gamma, number of steps of electron and number of steps of positron are scored.

Example 4.22. UI commands to define a scoring mesh and scorers

```
#
# define scoring mesh
#
/score/create/boxMesh boxMesh_1
/score/mesh/boxSize 100. 100. 100. cm
/score/mesh/nBin 30 30 30
#
# define scorers and filters
#
/score/quantity/energyDeposit eDep
/score/quantity/nOfStep nOfStepGamma
/score/filter/particle gammaFilter gamma
/score/quantity/nOfStep nOfStepEMinus
/score/filter/particle eMinusFilter e-
/score/quantity/nOfStep nOfStepEPlus
/score/filter/particle ePlusFilter e+
#
/score/close
#
```

4.8.3. Drawing scores

Once scores are filled, it is possible to visualize the scores. The score is drawn on top of the mass geometry with the current visualization settings.

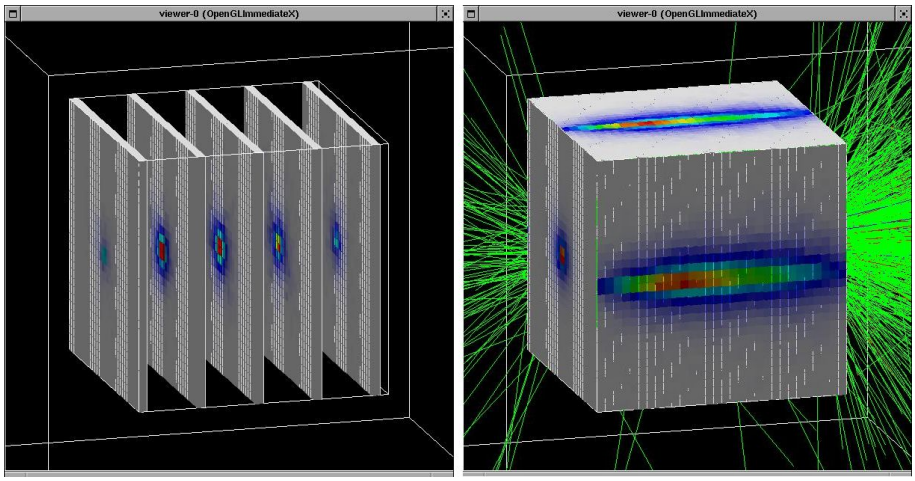


Figure 4.10. Drawing scores in slices (left) and projection (right)

By default, entries are linearly mapped to colors (gray - blue - green - red). This color mapping is implemented in `G4DefaultLinearColorMap` class, and registered to `G4ScoringManager` with the color map name

"defaultLinearColorMap". The user may alternate color map by implementing a customised color map class derived from G4VScoreColorMap and register it to G4ScoringManager. Then, for each draw command, one can specify the preferred color map.

4.8.4. Writing scores to a file

It is possible to dump a score in a mesh (/score/dumpQuantityToFile command) or all scores in a mesh (/score/dumpAllQuantitiesToFile command) to a file. The default file format is the simple CSV. To alternate the file format, one should overwrite G4VScoreWriter class and register it to G4ScoringManager. Please refer to /examples/extended/runAndEvent/RE03 for details.

Chapter 5. Tracking and Physics

5.1. Tracking

5.1.1. Basic Concepts

Philosophy of Tracking

All Geant4 processes, including the transportation of particles, are treated generically. In spite of the name "*tracking*", particles are not *transported* in the tracking category. *G4TrackingManager* is an interface class which brokers transactions between the event, track and tracking categories. An instance of this class handles the message passing between the upper hierarchical object, which is the event manager, and lower hierarchical objects in the tracking category. The event manager is a singleton instance of the *G4EventManager* class.

The tracking manager receives a track from the event manager and takes the actions required to finish tracking it. *G4TrackingManager* aggregates the pointers to *G4SteppingManager, G4Trajectory* and *G4UserTrackingAction*. Also there is a "use" relation to *G4Track* and *G4Step*.

G4SteppingManager plays an essential role in tracking the particle. It takes care of all message passing between objects in the different categories relevant to transporting a particle (for example, geometry and interactions in matter). Its public method `Stepping()` steers the stepping of the particle. The algorithm to handle one step is given below.

1. If the particle stop (i.e. zero kinetic energy), each active atRest process proposes a step length in time based on the interaction it describes. And the process proposing the smallest step length will be invoked.
2. Each active discrete or continuous process must propose a step length based on the interaction it describes. The smallest of these step lengths is taken.
3. The geometry navigator calculates "Safety", the distance to the next volume boundary. If the minimum physical-step-length from the processes is shorter than "Safety", the physical-step-length is selected as the next step length. In this case, no further geometrical calculations will be performed.
4. If the minimum physical-step-length from the processes is longer than "Safety", the distance to the next boundary is re-calculated.
5. The smaller of the minimum physical-step-length and the geometric step length is taken.
6. All active continuous processes are invoked. Note that the particle's kinetic energy will be updated only after all invoked processes have completed. The change in kinetic energy will be the sum of the contributions from these processes.
7. The current track properties are updated before discrete processes are invoked. In the same time, the secondary particles created by processes are stored in SecondaryList. The updated properties are:
   - updating the kinetic energy of the current track particle (note that 'sumEnergyChange' is the sum of the energy difference before and after each process invocation)
   - updating position and time
8. The kinetic energy of the particle is checked to see whether or not it has been terminated by a continuous process. If the kinetic energy goes down to zero, atRest processes will be applied at the next step if applicable.
9. The discrete process is invoked. After the invocation,
   - the energy, position and time of the current track particle are updated, and
   - the secondaries are stored in SecondaryList.
10. The track is checked to see whether or not it has been terminated by the discrete process.
11. "Safety" is updated.
12. If the step was limited by the volume boundary, push the particle into the next volume.
13. Invoke the user intervention *G4UserSteppingAction*.
14. Handle hit information.
15. Save data to Trajectory.
16. Update the mean free paths of the discrete processes.
17. If the parent particle is still alive, reset the maximum interaction length of the discrete process which has occurred.
18. One step completed.

What is a Process?

Only processes can change information of *G4Track* and add secondary tracks via `ParticleChange`. *G4VProcess* is a base class of all processes and it has 3 kinds of `DoIt` and `GetPhysicalInteraction` methods in order to describe interactions generically. If a user want to modify information of *G4Track*, he (or she) SHOULD create a special process for the purpose and register the process to the particle.

What is a Track?

G4Track keeps 'current' information of the particle. (i.e. energy,momentum, position ,time and so on) and has 'static' information (i.e. mass, charge, life and so on) also. Note that *G4Track* keeps information at the beginning of the step while the `AlongStepDoIt`s are being invoked for the step in progress.After finishing all `AlongStepDoIt`s, *G4Track* is updated. On the other hand, *G4Track* is updated after each invocation of a `PostStepDoIt`.

What is a Step?

G4Step stores the transient information of a step. This includes the two endpoints of the step, `PreStepPoint` and `PostStepPoint`, which contain the points' coordinates and the volumes containing the points. *G4Step* also stores the change in track properties between the two points. These properties, such as energy and momentum, are updated as the various active processes are invoked.

What is a ParticleChange?

Processes do NOT change any information of *G4Track* directly in their `DoIt`. Instead, they proposes changes as a result of interactions by using `ParticleChange`. After each `DoIt`, `ParticleChange` updates `PostStepPoint` based on proposed changes. Then, *G4Track* is updated after finishing all `AlongStepDoIt`s and after each `PostStepDoIt`.

5.1.2. Access to Track and Step Information

How to Get Track Information

Track information may be accessed by invoking various `Get` methods provided in the *G4Track* class. For details, see the **Software Reference Manual**. Typical information available includes:

- (x,y,z)
- Global time (time since the event was created)
- Local time (time since the track was created)
- Proper time (time in its rest frame since the track was created)
- Momentum direction (unit vector)
- Kinetic energy
- Accumulated geometrical track length
- Accumulated true track length
- Pointer to dynamic particle
- Pointer to physical volume
- Track ID number
- Track ID number of the parent
- Current step number
- Track status
- (x,y,z) at the start point (vertex position) of the track
- Momentum direction at the start point (vertex position) of the track
- Kinetic energy at the start point (vertex position) of the track
- Pinter to the process which created the current track

How to Get Step Information

Step and step-point information can be retrieved by invoking various `Get` methods provided in the *G4Step*/ *G4StepPoint* classes. For details, see the **Software Reference Manual**.

Information in *G4Step* includes:

- Pointers to `PreStep` and `PostStepPoint`
- Geometrical step length (step length before the correction of multiple scattering)
- True step length (step length after the correction of multiple scattering)
- Increment of position and time between `PreStepPoint` and `PostStepPoint`
- Increment of momentum and energy between `PreStepPoint` and `PostStepPoint`. (Note: to get the energy deposited in the step, you cannot use this 'Delta energy'. You have to use 'Total energy deposit' as below.)
- Pointer to `G4Track`
- Total energy deposited during the step - this is the sum of
  - the energy deposited by the energy loss process, and
  - the energy lost by secondaries which have NOT been generated because each of their energies was below the cut threshold
- Energy deposited not by ionization during the step

Information in *G4StepPoint* (`PreStepPoint` and `PostStepPoint`) includes:

- (x, y, z, t)
- (px, py, pz, Ek)
- Momentum direction (unit vector)
- Pointers to physical volumes
- Safety
- Beta, gamma
- Polarization
- Step status
- Pointer to the physics process which defined the current step and its `DoIt` type
- Pointer to the physics process which defined the previous step and its `DoIt` type
- Total track length
- Global time (time since the current event began)
- Local time (time since the current track began)
- Proper time

How to Get "particle change"

Particle change information can be accessed by invoking various `Get` methods provided in the *G4ParticleChange* class. Typical information available includes (for details, see the **Software Reference Manual**):

- final momentum direction of the parent particle
- final kinetic energy of the parent particle
- final position of the parent particle
- final global time of the parent particle
- final proper time of the parent particle
- final polarization of the parent particle
- status of the parent particle (*G4TrackStatus*)
- true step length (this is used by multiple scattering to store the result of the transformation from the geometrical step length to the true step length)
- local energy deposited - this consists of either
  - energy deposited by the energy loss process, or
  - the energy lost by secondaries which have NOT been generated because each of their energies was below the cut threshold.
- number of secondaries particles
- list of secondary particles (list of *G4Track*)

5.1.3. Handling of Secondary Particles

Secondary particles are passed as *G4Track*s from a physics process to tracking. *G4ParticleChange* provides the following four methods for a physics process:

- `AddSecondary( G4Track* aSecondary )`
- `AddSecondary( G4DynamicParticle* aSecondary )`
- `AddSecondary( G4DynamicParticle* aSecondary, G4ThreeVector position )`
- `AddSecondary( G4DynamicParticle* aSecondary, G4double time)`

In all but the first, the construction of *G4Track* is done in the methods using information given by the arguments.

5.1.4. User Actions

There are two classes which allow the user to intervene in the tracking. These are:

- *G4UserTrackingAction*, and
- *G4UserSteppingAction*.

Each provides methods which allow the user access to the Geant4 kernel at specific points in the tracking. For details, see the **Software Reference Manual**.

Note-1: Users SHOULD NOT (and CAN NOT) change *G4Track* in `UserSteppingAction`. Only the exception is the `TrackStatus`.

Note-2: Users have to be cautious to implement an unnatural/unphysical action in these user actions. See the section Killing Tracks in User Actions and Energy Conservation for more details.

5.1.5. Verbose Outputs

The verbose information output flag can be turned on or off. The amount of information printed about the track/step, from brief to very detailed, can be controlled by the value of the verbose flag, for example,

```
G4UImanager* UI = G4UImanager::GetUIpointer();

UI->ApplyCommand("/tracking/verbose 1");
```

5.1.6. Trajectory and Trajectory Point

G4Trajectory and G4TrajectoryPoint

G4Trajectory and *G4TrajectoryPoint* are default concrete classes provided by Geant4, which are derived from the *G4VTrajectory* and *G4VTrajectoryPoint* base classes, respectively. A *G4Trajectory* class object is created by *G4TrackingManager* when a *G4Track* is passed from the *G4EventManager*. *G4Trajectory* has the following data members:

- ID numbers of the track and the track's parent
- particle name, charge, and PDG code
- a collection of *G4TrajectoryPoint* pointers

G4TrajectoryPoint corresponds to a step point along the path followed by the track. Its position is given by a *G4ThreeVector*. A *G4TrajectoryPoint* class object is created in the *AppendStep()* method of *G4Trajectory* and this method is invoked by *G4TrackingManager* at the end of each step. The first point is created when the *G4Trajectory* is created, thus the first point is the original vertex.

The creation of a trajectory can be controlled by invoking *G4TrackingManager::SetStoreTrajectory(G4bool)*. The UI command */tracking/storeTrajectory _bool_* does the same. The user can set this flag for each individual track from his/her *G4UserTrackingAction::PreUserTrackingAction()* method.

> The user should not create trajectories for secondaries in a shower due to the large amount of memory consumed.

All the created trajectories in an event are stored in *G4TrajectoryContainer* class object and this object will be kept by *G4Event*. To draw or print trajectories generated in an event, the user may invoke the *DrawTrajectory()* or *Show-*

Trajectory() methods of *G4VTrajectory*, respectively, from his/her *G4UserEventAction::EndOfEventAction()*. The geometry must be drawn before the trajectory drawing. The color of the drawn trajectory depends on the particle charge:

- negative: red
- neutral: green
- positive: blue

> Due to improvements in *G4Navigator*, a track can execute more than one turn of its spiral trajectory without being broken into smaller steps as long as the trajectory does not cross a geometrical boundary. Thus a drawn trajectory may not be circular.

Customizing trajectory and trajectory point

G4Track and *G4Step* are transient classes; they are not available at the end of the event. Thus, the concrete classes *G4VTrajectory* and *G4VTrajectoryPoint* are the only ones a user may employ for end-of-event analysis or for persistency. As mentioned above, the default classes which Geant4 provides, i.e. *G4Trajectory* and *G4TrajectoryPoint*, have only very primitive quantities. The user can customize his/her own trajectory and trajectory point classes by deriving directly from the respective base classes.

To use the customized trajectory, the user must construct a concrete trajectory class object in the *G4UserTrackingAction::PreUserTrackingAction()* method and make its pointer available to *G4TrackingManager* by using the *SetTrajectory()* method. The customized trajectory point class object must be constructed in the *AppendStep()* method of the user's implementation of the trajectory class. This *AppendStep()* method will be invoked by *G4TrackingManager*.

To customize trajectory drawing, the user can override the *DrawTrajectory()* method in his/her own trajectory class.

When a customized version of G4Trajectory declares any new class variables, *operator new* and *operator delete* must be provided. It is also useful to check that the allocation size in *operator new* is equal to *sizeof(G4Trajectory)*. These two points do not apply to *G4VTrajectory* because it has no *operator new* or *operator delete*.

5.2. Physics Processes

Physics processes describe how particles interact with a material. Seven major categories of processes are provided by Geant4:

1. electromagnetic ,
2. hadronic ,
3. decay ,
4. photolepton-hadron ,
5. optical ,
6. parameterization and
7. transportation .

The generalization and abstraction of physics processes is a key issue in the design of Geant4. All physics processes are treated in the same manner from the tracking point of view. The Geant4 approach enables anyone to create a process and assign it to a particle type. This openness should allow the creation of processes for novel, domain-specific or customised purposes by individuals or groups of users.

Each process has two groups of methods which play an important role in tracking, `GetPhysicalInteractionLength` (GPIL) and `DoIt`. The GPIL method gives the step length from the current space-time point to the next space-time point. It does this by calculating the probability of interaction based on the process's cross section information. At the end of this step the `DoIt` method should be invoked. The `DoIt` method implements the details of the interaction, changing the particle's energy, momentum, direction and position, and producing secondary tracks if required. These changes are recorded as *G4VParticleChange* objects(see Particle Change).

G4VProcess

G4VProcess is the base class for all physics processes. Each physics process must implement virtual methods of *G4VProcess* which describe the interaction (DoIt) and determine when an interaction should occur (GPIL). In order to accommodate various types of interactions *G4VProcess* provides three `DoIt` methods:

- `G4VParticleChange* AlongStepDoIt( const G4Track& track, const G4Step& stepData )`

  This method is invoked while *G4SteppingManager* is transporting a particle through one step. The corresponding `AlongStepDoIt` for each defined process is applied for every step regardless of which process produces the minimum step length. Each resulting change to the track information is recorded and accumulated in *G4Step*. After all processes have been invoked, changes due to `AlongStepDoIt` are applied to *G4Track*, including the particle relocation and the safety update. Note that after the invocation of `AlongStepDoIt`, the endpoint of the *G4Track* object is in a new volume if the step was limited by a geometric boundary. In order to obtain information about the old volume, *G4Step* must be accessed, since it contains information about both endpoints of a step.
- `G4VParticleChange* PostStepDoIt( const G4Track& track, const G4Step& stepData )`

  This method is invoked at the end point of a step, only if its process has produced the minimum step length, or if the process is forced to occur. *G4Track* will be updated after each invocation of `PostStepDoIt`, in contrast to the `AlongStepDoIt` method.
- `G4VParticleChange* AtRestDoIt( const G4Track& track, const G4Step& stepData )`

  This method is invoked only for stopped particles, and only if its process produced the minimum step length or the process is forced to occur.

For each of the above `DoIt` methods *G4VProcess* provides a corresponding pure virtual GPIL method:

- `G4double PostStepGetPhysicalInteractionLength( const G4Track& track, G4double previousStepSize, G4ForceCondition* condition )`

  This method generates the step length allowed by its process. It also provides a flag to force the interaction to occur regardless of its step length.
- `G4double AlongStepGetPhysicalInteractionLength( const G4Track& track, G4double previousStepSize, G4double currentMinimumStep, G4double& proposedSafety, G4GPILSelection* selection )`

  This method generates the step length allowed by its process.
- `G4double AtRestGetPhysicalInteractionLength( const G4Track& track, G4ForceCondition* condition )`

  This method generates the step length in time allowed by its process. It also provides a flag to force the interaction to occur regardless of its step length.

Other pure virtual methods in *G4VProcess* follow:

- `virtual G4bool IsApplicable(const G4ParticleDefinition&)`

  returns true if this process object is applicable to the particle type.
- `virtual void PreparePhysicsTable(const G4ParticleDefinition&)` and
- `virtual void BuildPhysicsTable(const G4ParticleDefinition&)`

  is messaged by the process manager, whenever cross section tables should be prepared and rebuilt due to changing cut-off values. It is not mandatory if the process is not affected by cut-off values.
- `virtual void StartTracking()` and
- `virtual void EndTracking()`

  are messaged by the tracking manager at the beginning and end of tracking the current track.

Other base classes for processes

Specialized processes may be derived from seven additional virtual base classes which are themselves derived from *G4VProcess*. Three of these classes are used for simple processes:

G4VRestProcess
Processes using only the `AtRestDoIt` method.

example: neutron capture

G4VDiscreteProcess
Processes using only the `PostStepDoIt` method.

example: compton scattering, hadron inelastic interaction

The other four classes are provided for rather complex processes:

G4VContinuousDiscreteProcess
Processes using both `AlongStepDoIt` and `PostStepDoIt` methods.

example: transportation, ionisation(energy loss and delta ray)

G4VRestDiscreteProcess
Processes using both `AtRestDoIt` and `PostStepDoIt` methods.

example: positron annihilation, decay (both in flight and at rest)

G4VRestContinuousProcess
Processes using both `AtRestDoIt` and `AlongStepDoIt` methods.

G4VRestContinuousDiscreteProcess
Processes using `AtRestDoIt`, `AlongStepDoIt and` PostStepDoIt methods.

Particle change

G4VParticleChange and its descendants are used to store the final state information of the track, including secondary tracks, which has been generated by the `DoIt` methods. The instance of *G4VParticleChange* is the only object whose information is updated by the physics processes, hence it is responsible for updating the step. The stepping manager collects secondary tracks and only sends requests via particle change to update *G4Step*.

G4VParticleChange is introduced as an abstract class. It has a minimal set of methods for updating *G4Step* and handling secondaries. A physics process can therefore define its own particle change derived from *G4VParticleChange*. Three pure virtual methods are provided,

- `virtual G4Step* UpdateStepForAtRest( G4Step* step)`,
- `virtual G4Step* UpdateStepForAlongStep( G4Step* step )` and
- `virtual G4Step* UpdateStepForPostStep( G4Step* step)`,

which correspond to the three `DoIt` methods of *G4VProcess*. Each derived class should implement these methods.

5.2.1. Electromagnetic Interactions

This section summarizes the electromagnetic (EM) physics processes which are provided with Geant4. Extended information are avalable at EM web **pages**. For details on the implementation of these processes please refer to the **Physics Reference Manual**.

5.2.1.1. "Standard" Electromagnetic Processes

The following is a summary of the standard electromagnetic processes available in Geant4.

- Photon processes
  - Compton scattering (class name *G4ComptonScattering*)
  - Gamma conversion (also called pair production, class name *G4GammaConversion*)
  - Photo-electric effect (class name *G4PhotoElectricEffect*)
  - Muon pair production (class name *G4GammaConversionToMuons*)
- Electron/positron processes
  - Ionisation and delta ray production (class name *G4eIonisation*)
  - Bremsstrahlung (class name *G4eBremsstrahlung*)
  - Multiple scattering (class name *G4eMultipleScattering*)
  - Positron annihilation into two gammas (class name *G4eplusAnnihilation*)
  - Positron annihilation into two muons (class name *G4AnnihiToMuPair*)
  - Positron annihilation into hadrons (class name *G4eeToHadrons*)
- Muon processes
  - Bremsstrahlung (class name *G4MuBremsstrahlung*)
  - Ionisation and delta ray production (class name *G4MuIonisation*)
  - Multiple scattering (class name *G4MuMultipleScattering*)
  - e+e- pair production (class name *G4MuPairProduction*)
- Hadron/ion processes
  - Bremsstrahlung (class name *G4hBremsstrahlung*)
  - Ionisation (class name *G4hIonisation*)
  - e+e- pair production (class name *G4hPairProduction*)
  - Ionisation for ions (class name *G4ionIonisation*)
  - Multiple scattering (class name *G4hMultipleScattering*)
  - Ionisation for heavy exotic particles (class name *G4hhIonisation*)
  - Ionisation for classical magnetic monopole (class name *G4mplIonisation*)
- Coulomb scattering processes
  - Alternative process for simulation of single Coulomb scattering of all charged particles (class name *G4CoulombScattering*)
  - Alternative process for simulation of single Coulomb scattering of ions (class name *G4ScreenedNuclearRecoil*)
- Processes for simulation of polarized electron and gamma beams
  - Compton scattering of circularly polarized gamma beam on polarized target (class name *G4PolarizedCompton*)
  - Pair production induced by circularly polarized gamma beam (class name *G4PolarizedGammaConversion*)
  - Photo-electric effect induced by circularly polarized gamma beam (class name *G4PolarizedPhotoElectricEffect*)
  - Bremsstrahlung of polarized electrons and positrons (class name *G4ePolarizedBremsstrahlung*)
  - Ionisation of polarized electron and positron beam (class name *G4ePolarizedIonisation*)
  - Annihilation of polarized positrons (class name *G4eplusPolarizedAnnihilation*)
- Processes for simulation of X-rays and optical protons production by charged particles
  - Synchrotron radiation (class name *G4SynchrotronRadiation*)
  - Transition radiation (class name *G4TransitionRadiation*)
  - Cerenkov radiation (class name *G4Cerenkov*)
  - Scintillations (class name *G4Scintillation*)
- The processes described above use physics model classes, which may be combined according to particle energy. It is possible to change the energy range over which different models are valid, and to apply other models specific to particle type, energy range, and G4Region. The following alternative models are available:
  - Ionisation in thin absorbers (class name *G4PAIModel*)

It is recommended to use physics constructor classes provided with rederence physics lists ($G4INSTALL/source/physics_lists/builders):

- default EM physics (class name *G4EmStandardPhysics*)
- optional EM physics providing fast but less acurate electron transport due to "Simple" method of step limitation by multiple scattering, reduced step limitation by ionisation process and enabled "ApplyCuts" option (class name *G4EmStandardPhysics_option1*)
- Experimental EM physics with enabled "ApplyCuts" option, *G4WentzelVIModel* for muon multiple scattering (class name *G4EmStandardPhysics_option2*)

- EM physics for simulation with high accuracy due to "UseDistanceToBoundary" multiple scattering step limitation, reduced *finalRange* parameter of stepping function optimized per particle type, *G4WentzelVIModel* for muon multiple scattering and *G4IonParameterisedLossModel* for ion ionisation (class name *G4EmStandardPhysics_option3*)
- Combined Standard and Low-energy EM physics constructors based on the Option3 constructor; low-energy models are applied below 1 GeV:
  - Models based on Livermore data bases for electrons and gamma (*G4EmLivermorePhysics*);
  - Polarized models based on Livermore data bases for electrons and gamma (*G4EmLivermorePolarizedPhysics*);
  - Penelope models for electrons, positrons and gamma (*G4EmPenelopePhysics*);
  - Low-energy DNA physics (*G4EmDNAPhysics*).

Examples of the registration of these physics constructor and construction of alternative combinations of options are shown in novice, extended and advanced examples ($G4INSTALL/examples/extended/electromagnetic and $G4INSTALL/examples/advanced). Examples illustrating the use of electromagnetic processes are available as part of the Geant4 release.

Options are available for steering of electromagnetic processes. These options may be invoked either by UI commands or by the interface class G4EmProcessOptions. This class has the following public methods:

- SetLossFluctuations(G4bool)
- SetSubCutoff(G4bool, const G4Region* r=0)
- SetIntegral(G4bool)
- SetMinSubRange(G4double)
- SetMinEnergy(G4double)
- SetMaxEnergy(G4double)
- SetMaxEnergyForCSDARange(G4double)
- SetMaxEnergyForMuons(G4double)
- SetDEDXBinning(G4int)
- SetDEDXBinningForCSDARange(G4int)
- SetLambdaBinning(G4int)
- SetStepFunction(G4double, G4double)
- SetRandomStep(G4bool)
- SetApplyCuts(G4bool)
- SetSpline(G4bool)
- SetBuildCSDARange(G4bool)
- SetVerbose(G4int, const G4String name= "all")
- SetLambdaFactor(G4double)
- SetLinearLossLimit(G4double)
- ActivateDeexcitation(G4bool val, const G4Region* r = 0)
- SetMscStepLimitation(G4MscStepLimitType val)
- SetMscLateralDisplacement(G4bool val)
- SetSkin(G4double)
- SetMscRangeFactor(G4double)
- SetMscGeomFactor(G4double)
- SetLPMFlag(G4bool)
- SetBremsstrahlungTh(G4double)
- SetPolarAngleLimit(G4double)
- SetFactorForAngleLimit(G4double)

The corresponding UI command can be accessed in the UI subdirectory "/process/eLoss". The following types of step limitation by multiple scattering are available:

- fSimple - simplified step limitation as in g4 7.1 version (used in QGSP_BERT_EMV Physics List)
- fUseSafety - default
- fUseDistanceToBoundary - advance method of step limitation used in EM examples, required parameter *skin > 0*, should be used for setup without magnetic field

G4EmCalculator is a class which provides access to cross sections and stopping powers. This class can be used anywhere in the user code provided the physics list has already been initialised (G4State_Idle). G4EmCalculator has "Get" methods which can be applied to materials for which physics tables are already built, and "Compute" methods which can be applied to any material defined in the application or existing in the Geant4 internal database. The public methods of this class are:

- GetDEDX(kinEnergy,particle,material,G4Region region=0)
- GetRangeFromRestrictedDEDX(kinEnergy,particle,material,G4Region* region=0)
- GetCSDARange(kinEnergy,particle,material,G4Region* region=0)
- GetRange(kinEnergy,particle,material,G4Region* region=0)
- GetKinEnergy(range,particle,material,G4Region* region=0)
- GetCrosSectionPerVolume(kinEnergy,particle,material,G4Region* region=0)
- GetMeanFreePath(kinEnergy,particle,material,G4Region* region=0)
- PrintDEDXTable(particle)
- PrintRangeTable(particle)
- PrintInverseRangeTable(particle)
- ComputeDEDX(kinEnergy,particle,process,material,cut=DBL_MAX)
- ComputeElectronicDEDX(kinEnergy,particle,material,cut=DBL_MAX)
- ComputeNuclearDEDX(kinEnergy,particle,material,cut=DBL_MAX)
- ComputeTotalDEDX(kinEnergy,particle,material,cut=DBL_MAX)
- ComputeCrosSectionPerVolume(kinEnergy,particle,process,material,cut=0)
- ComputeCrosSectionPerAtom(kinEnergy,particle,process,Z,A,cut=0)
- ComputeMeanFreePath(kinEnergy,particle,process,material,cut=0)
- ComputeEnergyCutFromRangeCut(range,particle,material)
- FindParticle(const G4String&)
- FindIon(G4int Z, G4int A)
- FindMaterial(const G4String&)
- FindRegion(const G4String&)
- FindCouple(const G4Material*, const G4Region* region=0)
- SetVerbose(G4int)

For these interfaces, particles, materials, or processes may be pointers or strings with names.

5.2.1.2. Low Energy Electromagnetic Processes

A physical interaction is described by a process class which can handle physics models, described by model classes. The following is a summary of the Low Energy Electromagnetic physics models available in Geant4. Further information is available in the web pages of the Geant4 Low Energy Electromagnetic Physics Working Group, accessible from the Geant4 web site, “who we are” section, then “working groups”.

The physics content of these models is documented in the Geant4 Physics Reference Manual. They are based on the Livermore data library, on the ICRU73 data tables or on the Penelope Monte Carlo code. They adopt the same software design as the "standard" Geant4 electromagnetic models.

Examples of the registration of physics constructor with low-energy electromagnetic models are shown in Geant4 extended examples (`$G4INSTALL/examples/extended/electromagnetic`). Advanced examples (`$G4INSTALL/examples/advanced`) illustrate alternative instantiation of these processes. Both are available as part of the Geant4 release.

To use the low energy electromagnetic models, data files need to be copied by the user to his/her code repository. These files are distributed together with Geant4. The user should set the environment variable G4LEDATA to the directory where he/she has copied the files.

5.2.1.2.1. Livermore based models

- **Photon models**
  - Photo-electric effect (class *G4LivermorePhotoElectricModel*)

  - Polarized Photo-electric effect (class *G4LivermorePolarizedPhotoElectricModel*)
  - Compton scattering (class *G4LivermoreComptonModel*)
  - Polarized Compton scattering (class *G4LivermorePolarizedComptonModel*)
  - Rayleigh scattering (class *G4LivermoreRayleighModel*)
  - Polarized Rayleigh scattering (class *G4LivermorePolarizedRayleighModel*)
  - Gamma conversion (also called pair production, class *G4LivermoreGammaConversionModel*)
  - Polarized gamma conversion (class *G4LivermorePolarizedGammaConversionModel*)
- **Electron models**
  - Bremsstrahlung (class *G4LivermoreBremsstrahlungModel*)
  - Ionisation and delta ray production (class *G4LivermoreIonisationModel*)

Options can be set in the G4LivermorePhotoElectricModel class, that allow the use of alternative photoelectron angular generators:

- SetAngularGenerator(G4VPhotoElectricAngularDistribution* distribution);
- SetAngularGenerator(const G4String& name);

Currently three angular generators are available: G4PhotoElectricAngularGeneratorSimple, G4PhotoElectricAngularGeneratorSauterGavrilla and G4PhotoElectricAngularGeneratorPolarized. G4PhotoElectricAngularGeneratorSauterGavrilla is selected by default. G4PhotoElectricAngularGeneratorSimple, G4PhotoElectricAngularGeneratorSauterGavrilla and G4PhotoElectricAngularGeneratorPolarized can be set using respectively the strings "default", "standard" and "polarized".

Options are available in the G4LivermoreBremsstrahlungModel class, that allow the use of alternative bremsstrahlung angular generators:

- SetAngularGenerator(G4VBremAngularDistribution* distribution);
- SetAngularGenerator(const G4String& name);

Currently three angular generators are available: G4ModifiedTsai, 2BNGenerator and 2BSGenerator. G4ModifiedTsai is set by default, but it can be forced using the string "tsai". 2BNGenerator and 2BSGenerator can be set using the strings "2bs" and "2bn". Information regarding conditions of use, performance and energy limits of different models are available in the Physics Reference Manual .

Other options G4LivermoreBremsstrahlungModel class are:

- SetCutForLowEnSecPhotons(G4double)

Options are available in the G4LivermoreIonisationModel class:

- ActivateAuger(G4bool)
- SetCutForLowEnSecPhotons(G4double)
- SetCutForLowEnSecElectrons(G4double)

5.2.1.2.2. ICRU73 based ion model

Ionisation and delta ray production (class G4IonParametrisedLossModel)

The ion model uses ICRU 73 stopping powers, if corresponding ion-material combinations are covered by the ICRU 73 report (up to 1 GeV/nucleon), and otherwise applies a Bethe-Bloch based formalism. For compounds, ICRU 73 stopping powers are employed if the material name coincides with the name of Geant4 NIST materials (e.g. G4_WATER). Elemental materials are matched to the corresponding ICRU 73 stopping powers by means of the atomic number of the material. The material name may be arbitrary in this case. For a list of applicable materials, the user is referred to the ICRU 73 report.

The model requires data files to be copied by the user to his/her code repository. These files are distributed together with the Geant4 release. The user should set the environment variable G4LEDATA to the directory where he/she has copied the files.

The model is dedicated to be used with the G4ionIonisation process and its applicability is restricted to G4GenericIon particles. The ion model is not used by default by this process and must be instantiated and registered by the user:

```
G4ionIonisation* ionIoni = new G4ionIonisation();
ionIoni -> SetEmModel(new G4IonParametrisedLossModel());
```

5.2.1.2.3. Penelope based models

- **Photon models**
  - Compton scattering (class *G4PenelopeComptonModel*)
  - Rayleigh scattering (class *G4PenelopeRayleighModel*)
  - Gamma conversion (also called pair production, class *GPenelopeGammaConversionModel*)
  - Photo-electric effect (class *G4PenelopePhotoElectricModel*)
- **Electron models**
  - Bremsstrahlung (class *G4PenelopeBremsstrahlungModel*)
  - Ionisation and delta ray production (class *G4PenelopeIonisationModel*)
- **Positron models**
  - Bremsstrahlung (class *G4PenelopeBremsstrahlungModel*)
  - Ionisation and delta ray production (class *G4PenelopeIonisationModel*)
  - Positron annihilation (class *class G4PenelopeAnnihilationModel*)

All Penelope models can be applied up to a maximum energy of 100 GeV, although it is advisable not to use them above a few hundreds of MeV.

Options are available in the all Penelope Models, allowing to set (and retrieve) the verbosity level of the model, namely the amount of information which is printed on the screen.

- SetVerbosityLevel(G4int)
- GetVerbosityLevel()

The default verbosity level is 0 (namely, no textual output on the screen). The default value should be used in general for normal runs. Higher verbosity levels are suggested only for testing and debugging purposes.

The verbosity scale defined for all Penelope processes is the following:

- 0 = no printout on the screen (default)
- 1 = issue warnings only in the case of energy non-conservation in the final state (should never happen)
- 2 = reports full details on the energy budget in the final state
- 3 = writes also informations on cross section calculation, data file opening and sampling of atoms
- 4 = issues messages when entering in methods

Options are available in G4PenelopeComptonModel, G4PenelopePhotoElectricModel and G4PenelopeIonisationModel to enable or disable the usage of atomic de-excitation via the G4AtomicDeexcitation module.

- SetDeexcitationFlag(G4bool)
- DeexcitationFlag()

The default is “true”, namely vacancies in atomic shells produced by the interaction are handled by the G4AtomicDeexcitation module, possibly with the subsequent emission of fluorescence x-rays. If is set to “false” by the user, the energy released in the re-arrangement of atomic vacancies is treated in the model as a local energy deposit, without emission of secondary particles. The methods are actually inherited from G4VEmModel, so they work for all Penelope models; by the way, they have effect only in G4PenelopeComptonModel, G4PenelopePhotoElectricModel and G4PenelopeIonisationModel.

An option is also available in these models to enable the production of Auger electrons by the G4AtomicDeexcitation module ActivateAuger(G4bool). The default (coming from G4AtomicDeexcitation) is “false”, namely only fluorescence x-rays are emitted but not Auger electrons. One should notice that this option

has effect only if the usage of the atomic deexcitation is enabled. A warning message is printed if one tries to enable the emission of the Auger electrons after having disabled the atomic deexcitation via SetDeexcitationFlag(false).

5.2.1.3. Very Low energy Electromagnetic Processes (Geant4-DNA extension)

The Geant4 low energy electromagnetic Physics package has been extended down to energies of a few electron-Volts suitable for the simulation of radiation effects in liquid water for applications in microdosimetry at the cellular and sub-cellular level. These developments take place in the framework of the on-going Geant4-DNA project (see the web pages of the Geant4 Low Energy Electromagnetic Physics Working Group).

The Geant4-DNA process and model classes apply to electrons, protons, hydrogen, alpha particles and their charge states.

Electron processes and models

- Elastic scattering :
  - process class is G4DNAElastic
  - two alternative model classes are : G4DNAScreenedRutherfordElasticModel or G4DNAChampionElasticModel
- Excitation
  - process class is G4DNAExcitation
  - model class is G4DNAEmfietzoglouExcitationModel
- Ionisation
  - process class is G4DNAIonisation
  - model class is G4DNABornIonisationModel

Proton processes and models

- Excitation
  - process class is G4DNAExcitation
  - two complementary model classes are G4DNAMillerGreenExcitationModel (below 500 keV) and G4DNABornExcitationModel (above)
- Ionisation
  - process class is G4DNAIonisation
  - two complementary model classes are G4DNARuddIonisationModel (below 500 keV) and G4DNABornIonisationModel (above)
- Charge decrease
  - process class is G4DNAChargeDecrease
  - model class is G4DNADingfelderChargeDecreaseModel

Hydrogen processes and models

- Ionisation
  - process class is G4DNAIonisation
  - model class is G4DNARuddIonisationModel
- Charge increase
  - process class is G4DNAChargeIncrease
  - model class is G4DNADingfelderChargeIncreaseModel

Helium (neutral) processes and models

- Excitation
  - process class is G4DNAExcitation
  - model class is G4DNAMillerGreenExcitationModel
- Ionisation
  - process class is G4DNAIonisation
  - model class is G4DNARuddIonisationModel

- Charge increase
  - process class is G4DNAChargeIncrease
  - model class is G4DNADingfelderChargeIncreaseModel

Helium+ (ionized once) processes and models

- Excitation
  - process class is G4DNAExcitation
  - model class is G4DNAMillerGreenExcitationModel
- Ionisation
  - process class is G4DNAIonisation
  - model classes is G4DNARuddIonisationModel
- Charge increase
  - process class is G4DNAChargeIncrease
  - model classes is G4DNADingfelderChargeIncreaseModel
- Charge decrease
  - process class is G4DNAChargeDecrease
  - model classes is G4DNADingfelderChargeDecreaseModel

Helium++ (ionised twice) processes and models

- Excitation
  - process class is G4DNAExcitation
  - model classes is G4DNAMillerGreenExcitationModel
- Ionisation
  - process class is G4DNAIonisation
  - model classes is G4DNARuddIonisationModel
- Charge decrease
  - process class is G4DNAChargeDecrease
  - model classes is G4DNADingfelderChargeDecreaseModel

An example of the registration of these processes in a physics list is given here below and may be found in the microdosimetry advanced example.

```
#include "G4DNAElastic.hh"
#include "G4DNAChampionElasticModel.hh"
#include "G4DNAScreenedRutherfordElasticModel.hh"

#include "G4DNAExcitation.hh"
#include "G4DNAEmfietzoglouExcitationModel.hh"
#include "G4DNAMillerGreenExcitationModel.hh"
#include "G4DNABornExcitationModel.hh"

#include "G4DNAIonisation.hh"
#include "G4DNABornIonisationModel.hh"
#include "G4DNARuddIonisationModel.hh"

#include "G4DNAChargeDecrease.hh"
#include "G4DNADingfelderChargeDecreaseModel.hh"

#include "G4DNAChargeIncrease.hh"
#include "G4DNADingfelderChargeIncreaseModel.hh"

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo....

void PhysicsList::ConstructEM()
{
  theParticleIterator->reset();

  while( (*theParticleIterator)() )
  {

    G4ParticleDefinition* particle = theParticleIterator->value();
    G4ProcessManager* pmanager = particle->GetProcessManager();
    G4String particleName = particle->GetParticleName();
```

```
// DNA processes per particle type

    if (particleName == "e-") {

      G4DNAElastic* theDNAElasticProcess = new G4DNAElastic("e-_G4DNAElastic");
      theDNAElasticProcess->SetModel(new G4DNAChampionElasticModel());
      // or alternative model
      // theDNAElasticProcess->SetModel(new G4DNAScreenedRutherfordElasticModel());
      pmanager->AddDiscreteProcess(theDNAElasticProcess);

      pmanager->AddDiscreteProcess(new G4DNAExcitation("e-_G4DNAExcitation"));
      pmanager->AddDiscreteProcess(new G4DNAIonisation("e-_G4DNAIonisation"));

    } else if ( particleName == "proton" ) {

      pmanager->AddDiscreteProcess(new G4DNAExcitation("proton_G4DNAExcitation"));
      pmanager->AddDiscreteProcess(new G4DNAIonisation("proton_G4DNAIonisation"));
      pmanager->AddDiscreteProcess(new G4DNAChargeDecrease("proton_G4DNAChargeDecrease"));

    } else if ( particleName == "hydrogen" ) {

      pmanager->AddDiscreteProcess(new G4DNAIonisation("hydrogen_G4DNAIonisation"));
      pmanager->AddDiscreteProcess(new G4DNAChargeIncrease("hydrogen_G4DNAChargeIncrease"));

    } else if ( particleName == "alpha" ) {

      pmanager->AddDiscreteProcess(new G4DNAExcitation("alpha_G4DNAExcitation"));
      pmanager->AddDiscreteProcess(new G4DNAIonisation("alpha_G4DNAIonisation"));
      pmanager->AddDiscreteProcess(new G4DNAChargeDecrease("alpha_G4DNAChargeDecrease"));

    } else if ( particleName == "alpha+" ) {

      pmanager->AddDiscreteProcess(new G4DNAExcitation("alpha+_G4DNAExcitation"));
      pmanager->AddDiscreteProcess(new G4DNAIonisation("alpha+_G4DNAIonisation"));
      pmanager->AddDiscreteProcess(new G4DNAChargeDecrease("alpha+_G4DNAChargeDecrease"));
      pmanager->AddDiscreteProcess(new G4DNAChargeIncrease("alpha+_G4DNAChargeIncrease"));

    } else if ( particleName == "helium" ) {

      pmanager->AddDiscreteProcess(new G4DNAExcitation("helium_G4DNAExcitation"));
      pmanager->AddDiscreteProcess(new G4DNAIonisation("helium_G4DNAIonisation"));
      pmanager->AddDiscreteProcess(new G4DNAChargeIncrease("helium_G4DNAChargeIncrease"));

    }

  } // Loop on particles
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo....
```

Note that in the above example, "alpha" particles are helium atoms ionised twice and "helium" particles are neutral helium atoms. The definition of particles in the physics list may be for example implemented as follows :

```
//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

#include "G4DNAGenericIonsManager.hh"
void PhysicsList::ConstructBaryons()
{
// construct baryons ---
// Geant4 DNA particles
G4GenericIon::GenericIonDefinition() ;
G4DNAGenericIonsManager * genericIonsManager;
genericIonsManager=G4DNAGenericIonsManager::Instance();
genericIonsManager->GetIon("alpha++");
genericIonsManager->GetIon("alpha+");
genericIonsManager->GetIon("helium");
genericIonsManager->GetIon("hydrogen");
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......
```

To run the Geant4-DNA extension, data files need to be copied by the user to his/her code repository. These files are distributed together with the Geant4 release. The user should set the environment variable G4LEDATA to the directory where he/she has copied the files.

5.2.2. Hadronic Interactions

This section briefly introduces the hadronic physics processes installed in Geant4. For details of the implementation of hadronic interactions available in Geant4, please refer to the **Physics Reference Manual**.

5.2.2.1. Treatment of Cross Sections

Cross section data sets

Each hadronic process object (derived from *G4HadronicProcess*) may have one or more cross section data sets associated with it. The term "data set" is meant, in a broad sense, to be an object that encapsulates methods and data for calculating total cross sections for a given process. The methods and data may take many forms, from a simple equation using a few hard-wired numbers to a sophisticated parameterisation using large data tables. Cross section data sets are derived from the abstract class *G4VCrossSectionDataSet*, and are required to implement the following methods:

```
G4bool IsApplicable( const G4DynamicParticle*, const G4Element* )
```

This method must return `True` if the data set is able to calculate a total cross section for the given particle and material, and `False` otherwise.

```
G4double GetCrossSection( const G4DynamicParticle*, const G4Element* )
```

This method, which will be invoked only if `True` was returned by `IsApplicable`, must return a cross section, in Geant4 default units, for the given particle and material.

```
void BuildPhysicsTable( const G4ParticleDefinition& )
```

This method may be invoked to request the data set to recalculate its internal database or otherwise reset its state after a change in the cuts or other parameters of the given particle type.

```
void DumpPhysicsTable( const G4ParticleDefinition& ) = 0
```

This method may be invoked to request the data set to print its internal database and/or other state information, for the given particle type, to the standard output stream.

Cross section data store

Cross section data sets are used by the process for the calculation of the physical interaction length. A given cross section data set may only apply to a certain energy range, or may only be able to calculate cross sections for a particular type of particle. The class *G4CrossSectionDataStore* has been provided to allow the user to specify, if desired, a series of data sets for a process, and to arrange the priority of data sets so that the appropriate one is used for a given energy range, particle, and material. It implements the following public methods:

```
G4CrossSectionDataStore()

~G4CrossSectionDataStore()
```

and

```
G4double GetCrossSection( const G4DynamicParticle*, const G4Element* )
```

For a given particle and material, this method returns a cross section value provided by one of the collection of cross section data sets listed in the data store object. If there are no known data sets, a `G4Exception` is thrown and `DBL_MIN` is returned. Otherwise, each data set in the list is queried, in reverse list order, by invoking its `IsApplicable` method for the given particle and material. The first data set object that responds positively

will then be asked to return a cross section value via its `GetCrossSection` method. If no data set responds positively, a `G4Exception` is thrown and `DBL_MIN` is returned.

```
void AddDataSet( G4VCrossSectionDataSet* aDataSet )
```

This method adds the given cross section data set to the end of the list of data sets in the data store. For the evaluation of cross sections, the list has a LIFO (Last In First Out) priority, meaning that data sets added later to the list will have priority over those added earlier to the list. Another way of saying this, is that the data store, when given a `GetCrossSection` request, does the `IsApplicable` queries in the reverse list order, starting with the last data set in the list and proceeding to the first, and the first data set that responds positively is used to calculate the cross section.

```
void BuildPhysicsTable( const G4ParticleDefinition& aParticleType )
```

This method may be invoked to indicate to the data store that there has been a change in the cuts or other parameters of the given particle type. In response, the data store will invoke the `BuildPhysicsTable` of each of its data sets.

```
void DumpPhysicsTable( const G4ParticleDefinition& )
```

This method may be used to request the data store to invoke the `DumpPhysicsTable` method of each of its data sets.

Default cross sections

The defaults for total cross section data and calculations have been encapsulated in the singleton class *G4HadronCrossSections*. Each hadronic process: *G4HadronInelasticProcess*, *G4HadronElasticProcess*, *G4HadronFissionProcess*, and *G4HadronCaptureProcess*, comes already equipped with a cross section data store and a default cross section data set. The data set objects are really just shells that invoke the singleton *G4HadronCrossSections* to do the real work of calculating cross sections.

The default cross sections can be overridden in whole or in part by the user. To this end, the base class *G4HadronicProcess* has a ``get" method:

```
G4CrossSectionDataStore* GetCrossSectionDataStore()
```

which gives public access to the data store for each process. The user's cross section data sets can be added to the data store according to the following framework:

```
G4Hadron...Process aProcess(...)

MyCrossSectionDataSet myDataSet(...)

aProcess.GetCrossSectionDataStore()->AddDataSet( &MyDataSet )
```

The added data set will override the default cross section data whenever so indicated by its `IsApplicable` method.

In addition to the ``get" method, *G4HadronicProcess* also has the method

```
void SetCrossSectionDataStore( G4CrossSectionDataStore* )
```

which allows the user to completely replace the default data store with a new data store.

It should be noted that a process does not send any information about itself to its associated data store (and hence data set) objects. Thus, each data set is assumed to be formulated to calculate cross sections for one and only one type of process. Of course, this does not prevent different data sets from sharing common data and/or calculation methods, as in the case of the *G4HadronCrossSections* class mentioned above. Indeed, *G4VCrossSectionDataSet*

specifies only the abstract interface between physics processes and their data sets, and leaves the user free to implement whatever sort of underlying structure is appropriate.

The current implementation of the data set *G4HadronCrossSections* reuses the total cross-sections for inelastic and elastic scattering, radiative capture and fission as used with **GHEISHA** to provide cross-sections for calculation of the respective mean free paths of a given particle in a given material.

Cross-sections for low energy neutron transport

The cross section data for low energy neutron transport are organized in a set of files that are read in by the corresponding data set classes at time zero. Hereby the file system is used, in order to allow highly granular access to the data. The ``root" directory of the cross-section directory structure is accessed through an environment variable, `NeutronHPCrossSections`, which is to be set by the user. The classes accessing the total cross-sections of the individual processes, i.e., the cross-section data set classes for low energy neutron transport, are *G4NeutronHPElasticData*, *G4NeutronHPCaptureData*, *G4NeutronHPFissionData*, and *G4NeutronHPInelasticData*.

For detailed descriptions of the low energy neutron total cross-sections, they may be registered by the user as described above with the data stores of the corresponding processes for neutron interactions.

It should be noted that using these total cross section classes does not require that the neutron_hp models also be used. It is up to the user to decide whethee this is desirable or not for his particular problem.

A prototype of the compact version of neutron cross sections derived from HP database are provided with new classes *G4NeutronHPElasticData*, *G4NeutronCaptureXS*, *G4NeutronElasticXS*, and *G4NeutronInelasticXS*.

5.2.2.2. Hadrons at Rest

List of implemented "Hadron at Rest" processes

The following process classes have been implemented:

- pi- absorption (class name *G4PionMinusAbsorptionAtRest* or *G4PiMinusAbsorptionAtRest*)
- kaon- absorption (class name *G4KaonMinusAbsorptionAtRest* or *G4KaonMinusAbsorption*)
- neutron capture (class name *G4NeutronCaptureAtRest*)
- anti-proton annihilation (class name *G4AntiProtonAnnihilationAtRest*)
- anti-neutron annihilation (class name *G4AntiNeutronAnnihilationAtRest*)
- mu- capture (class name *G4MuonMinusCaptureAtRest*)
- alternative CHIPS model for any negativly charged particle (class name *G4QCaptureAtRest*)

Obviously the last process does not, strictly speaking, deal with a ``hadron at rest". It does, nonetheless, share common features with the others in the above list because of the implementation model chosen. The differences between the alternative implementation for kaon and pion absorption concern the fast part of the emitted particle spectrum. G4PiMinusAbsorptionAtRest, and G4KaonMinusAbsorptionAtRest focus especially on a good description of this part of the spectrum.

Implementation Interface to Geant4

All of these classes are derived from the abstract class *G4VRestProcess*. In addition to the constructor and destructor methods, the following public methods of the abstract class have been implemented for each of the above six processes:

- `AtRestGetPhysicalInteractionLength( const G4Track&, G4ForceCondition* )`

  This method returns the time taken before the interaction actually occurs. In all processes listed above, except for muon capture, a value of zero is returned. For the muon capture process the muon capture lifetime is returned.
- `AtRestDoIt( const G4Track&, const G4Step&)`

  This method generates the secondary particles produced by the process.
- `IsApplicable( const G4ParticleDefinition& )`

This method returns the result of a check to see if the process is possible for a given particle.

Example of how to use a hadron at rest process

Including a ``hadron at rest'' process for a particle, a pi- for example, into the Geant4 system is straightforward and can be done in the following way:

- create a process:

```
theProcess = new G4PionMinusAbsorptionAtRest();
```

- register the process with the particle's process manager:

```
theParticleDef = G4PionMinus::PionMinus();
G4ProcessManager* pman = theParticleDef->GetProcessManager();
pman->AddRestProcess( theProcess );
```

5.2.2.3. Hadrons in Flight

What processes do you need?

For hadrons in motion, there are four physics process classes. Table 5.1 shows each process and the particles for which it is relevant.

G4HadronElasticProcess	pi+, pi-, K^+, K^0_S, K^0_L, K^-, p, p-bar, n, n-bar, lambda, lambda-bar, $Sigma^+$, $Sigma^-$, $Sigma^+$-bar, $Sigma^-$-bar, Xi^0, Xi^-, Xi^0-bar, Xi^--bar
G4HadronInelasticProcess	pi+, pi-, K^+, K^0_S, K^0_L, K^-, p, p-bar, n, n-bar, lambda, lambda-bar, $Sigma^+$, $Sigma^-$, $Sigma^+$-bar, $Sigma^-$-bar, Xi^0, Xi^-, Xi^0-bar, Xi^--bar
G4HadronFissionProcess	all
G4CaptureProcess	n, n-bar

Table 5.1. Hadronic processes and relevant particles.

How to register Models

To register an inelastic process model for a particle, a proton for example, first get the pointer to the particle's process manager:

```
G4ParticleDefinition *theProton = G4Proton::ProtonDefinition();
G4ProcessManager *theProtonProcMan = theProton->GetProcessManager();
```

Create an instance of the particle's inelastic process:

```
G4ProtonInelasticProcess *theProtonIEProc = new G4ProtonInelasticProcess();
```

Create an instance of the model which determines the secondaries produced in the interaction, and calculates the momenta of the particles:

```
G4LEProtonInelastic *theProtonIE = new G4LEProtonInelastic();
```

Register the model with the particle's inelastic process:

```
theProtonIEProc->RegisterMe( theProtonIE );
```

Finally, add the particle's inelastic process to the list of discrete processes:

```
   theProtonProcMan->AddDiscreteProcess( theProtonIEProc );
```

The particle's inelastic process class, *G4ProtonInelasticProcess* in the example above, derives from the *G4HadronicInelasticProcess* class, and simply defines the process name and calls the *G4HadronicInelasticProcess* constructor. All of the specific particle inelastic processes derive from the *G4HadronicInelasticProcess* class, which calls the `PostStepDoIt` function, which returns the particle change object from the *G4HadronicProcess* function `GeneralPostStepDoIt`. This class also gets the mean free path, builds the physics table, and gets the microscopic cross section. The *G4HadronicInelasticProcess* class derives from the *G4HadronicProcess* class, which is the top level hadronic process class. The *G4HadronicProcess* class derives from the *G4VDiscreteProcess* class. The inelastic, elastic, capture, and fission processes derive from the *G4HadronicProcess* class. This pure virtual class also provides the energy range manager object and the `RegisterMe` access function.

A sample case for the proton's inelastic interaction model class is shown in Example 5.1, where `G4LEProtonInelastic.hh` is the name of the include file:

Example 5.1. An example of a proton inelastic interaction model class.

```
 ---------------------------- include file -----------------------------------------

#include "G4InelasticInteraction.hh"
 class G4LEProtonInelastic : public G4InelasticInteraction
 {
 public:
    G4LEProtonInelastic() : G4InelasticInteraction()
    {
      SetMinEnergy( 0.0 );
      SetMaxEnergy( 25.*GeV );
    }
    ~G4LEProtonInelastic() { }
    G4ParticleChange *ApplyYourself( const G4Track &aTrack,
                                     G4Nucleus &targetNucleus );
 private:
    void CascadeAndCalculateMomenta( required arguments );
 };

 ---------------------------- source file ------------------------------------------

 #include "G4LEProtonInelastic.hh"
 G4ParticleChange *
  G4LEProton Inelastic::ApplyYourself( const G4Track &aTrack,
                                       G4Nucleus &targetNucleus )
  {
    theParticleChange.Initialize( aTrack );
    const G4DynamicParticle *incidentParticle = aTrack.GetDynamicParticle();
    // create the target particle
    G4DynamicParticle *targetParticle = targetNucleus.ReturnTargetParticle();
    CascadeAndCalculateMomenta( required arguments )
    { ... }
    return &theParticleChange;
  }
```

The `CascadeAndCalculateMomenta` function is the bulk of the model and is to be provided by the model's creator. It should determine what secondary particles are produced in the interaction, calculate the momenta for all the particles, and put this information into the *ParticleChange* object which is returned.

The *G4LEProtonInelastic* class derives from the *G4InelasticInteraction* class, which is an abstract base class since the pure virtual function `ApplyYourself` is not defined there. *G4InelasticInteraction* itself derives from the *G4HadronicInteraction* abstract base class. This class is the base class for all the model classes. It sorts out the energy range for the models and provides class utilities. The *G4HadronicInteraction* class provides the `Set/GetMinEnergy` and the `Set/GetMaxEnergy` functions which determine the minimum and maximum energy range for the model. An energy range can be set for a specific element, a specific material, or for general applicability:

```
 void SetMinEnergy( G4double anEnergy, G4Element *anElement )
 void SetMinEnergy( G4double anEnergy, G4Material *aMaterial )
```

```
void SetMinEnergy( const G4double anEnergy )
void SetMaxEnergy( G4double anEnergy, G4Element *anElement )
void SetMaxEnergy( G4double anEnergy, G4Material *aMaterial )
void SetMaxEnergy( const G4double anEnergy )
```

Which models are there, and what are the defaults

In Geant4, any model can be run together with any other model without the need for the implementation of a special interface, or batch suite, and the ranges of applicability for the different models can be steered at initialisation time. This way, highly specialised models (valid only for one material and particle, and applicable only in a very restricted energy range) can be used in the same application, together with more general code, in a coherent fashion.

Each model has an intrinsic range of applicability, and the model chosen for a simulation depends very much on the use-case. Consequently, there are no ``defaults''. However, physics lists are provided which specify sets of models for various purposes.

Three types of hadronic shower models have been implemented: parametrisation driven models, data driven models, and theory driven models.

- Parametrisation driven models are used for all processes pertaining to particles coming to rest, and interacting with the nucleus. For particles in flight, two sets of models exist for inelastic scattering; low energy, and high energy models. Both sets are based originally on the **GHEISHA** package of Geant3.21, and the original approaches to primary interaction, nuclear excitation, intra-nuclear cascade and evaporation is kept. The models are located in the sub-directories `hadronics/models/low_energy` and `hadronics/models/high_energy`. The low energy models are targeted towards energies below 20 GeV; the high energy models cover the energy range from 20 GeV to O(TeV). Fission, capture and coherent elastic scattering are also modeled through parametrised models.
- Data driven models are available for the transport of low energy neutrons in matter in sub-directory `hadronics/models/neutron_hp`. The modeling is based on the data formats of **ENDF/B-VI**, and all distributions of this standard data format are implemented. The data sets used are selected from data libraries that conform to these standard formats. The file system is used in order to allow granular access to, and flexibility in, the use of the cross sections for different isotopes, and channels. The energy coverage of these models is from thermal energies to 20 MeV.
- Theory driven models are available for inelastic scattering in a first implementation, covering the full energy range of LHC experiments. They are located in sub-directory `hadronics/models/generator`. The current philosophy implies the usage of parton string models at high energies, of intra-nuclear transport models at intermediate energies, and of statistical break-up models for de-excitation.

5.2.3. Particle Decay Process

This section briefly introduces decay processes installed in Geant4. For details of the implementation of particle decays, please refer to the **Physics Reference Manual**.

5.2.3.1. Particle Decay Class

Geant4 provides a *G4Decay* class for both ``at rest'' and ``in flight'' particle decays. *G4Decay* can be applied to all particles except:

massless particles, i.e.,
```
G4ParticleDefinition::thePDGMass <= 0
```

particles with ``negative'' life time, i.e.,
```
G4ParticleDefinition::thePDGLifeTime < 0
```

shortlived particles, i.e.,
```
G4ParticleDefinition::fShortLivedFlag = True
```

Decay for some particles may be switched on or off by using `G4ParticleDefinition::SetPDGStable()` as well as `ActivateProcess()` and `InActivateProcess()` methods of *G4ProcessManager*.

G4Decay proposes the step length (or step time for `AtRest`) according to the lifetime of the particle unless `PreAssignedDecayProperTime` is defined in *G4DynamicParticle*.

The *G4Decay* class itself does not define decay modes of the particle. Geant4 provides two ways of doing this:

- using *G4DecayChannel* in *G4DecayTable*, and
- using `thePreAssignedDecayProducts` of *G4DynamicParticle*

The *G4Decay* class calculates the `PhysicalInteractionLength` and boosts decay products created by *G4VDecayChannel* or event generators. See below for information on the determination of the decay modes.

An object of *G4Decay* can be shared by particles. Registration of the decay process to particles in the `ConstructPhysics` method of *PhysicsList* (see Section 2.5.3) is shown in Example 5.2.

Example 5.2. Registration of the decay process to particles in the `ConstructPhysics` method of *PhysicsList*.

```
#include "G4Decay.hh"
void ExN02PhysicsList::ConstructGeneral()
{
  // Add Decay Process
  G4Decay* theDecayProcess = new G4Decay();
  theParticleIterator->reset();
  while( (*theParticleIterator)() ){
    G4ParticleDefinition* particle = theParticleIterator->value();
    G4ProcessManager* pmanager = particle->GetProcessManager();
    if (theDecayProcess->IsApplicable(*particle)) {
      pmanager ->AddProcess(theDecayProcess);
      // set ordering for PostStepDoIt and AtRestDoIt
      pmanager ->SetProcessOrdering(theDecayProcess, idxPostStep);
      pmanager ->SetProcessOrdering(theDecayProcess, idxAtRest);
    }
  }
}
```

5.2.3.2. Decay Table

Each particle has its *G4DecayTable*, which stores information on the decay modes of the particle. Each decay mode, with its branching ratio, corresponds to an object of various ``decay channel'' classes derived from *G4VDecayChannel*. Default decay modes are created in the constructors of particle classes. For example, the decay table of the neutral pion has *G4PhaseSpaceDecayChannel* and *G4DalitzDecayChannel* as follows:

```
  // create a decay channel
  G4VDecayChannel* mode;
  // pi0 -> gamma + gamma
  mode = new G4PhaseSpaceDecayChannel("pi0",0.988,2,"gamma","gamma");
  table->Insert(mode);
  // pi0 -> gamma + e+ + e-
  mode = new G4DalitzDecayChannel("pi0",0.012,"e-","e+");
  table->Insert(mode);
```

Decay modes and branching ratios defined in Geant4 are listed in Section 5.3.2.

Branching ratios and life time can be set in tracking time.

```
  // set lifetime
  G4Neutron::Neutron()->SetPDGLifeTime(885.7*second);
  // allow neutron decay
  G4Neutron::Neutron()->SetPDGStable(false);
```

Branching ratios and life time can be modified by using user commands, also.

Example: Set 100% br for dalitz decay of pi0

```
Idle> /particle/select pi0
Idle> /particle/property/decay/select 0
Idle> /particle/property/decay/br 0
Idle> /particle/property/decay/select 1
Idle> /particle/property/decay/br 1
Idle> /particle/property/decay/dump
      G4DecayTable:  pi0
         0:  BR:  0  [Phase Space]   :   gamma gamma
         1:  BR:  1  [Dalitz Decay]  :   gamma e- e+
```

5.2.3.3. Pre-assigned Decay Modes by Event Generators

Decays of heavy flavor particles such as B mesons are very complex, with many varieties of decay modes and decay mechanisms. There are many models for heavy particle decay provided by various event generators and it is impossible to define all the decay modes of heavy particles by using *G4VDecayChannel*. In other words, decays of heavy particles cannot be defined by the Geant4 decay process, but should be defined by event generators or other external packages. Geant4 provides two ways to do this: `pre-assigned decay mode` and `external decayer`.

In the latter approach, the class *G4VExtDecayer* is used for the interface to an external package which defines decay modes for a particle. If an instance of *G4VExtDecayer* is attached to *G4Decay*, daughter particles will be generated by the external decay handler.

In the former case, decays of heavy particles are simulated by an event generator and the primary event contains the decay information. *G4VPrimaryGenerator* automatically attaches any daughter particles to the parent particle as the PreAssignedDecayProducts member of *G4DynamicParticle*. *G4Decay* adopts these pre-assigned daughter particles instead of asking *G4VDecayChannel* to generate decay products.

In addition, the user may assign a `pre-assigned` decay time for a specific track in its rest frame (i.e. decay time is defined in the proper time) by using the *G4PrimaryParticle::SetProperTime()* method. *G4VPrimaryGenerator* sets the PreAssignedDecayProperTime member of *G4DynamicParticle*. *G4Decay* uses this decay time instead of the life time of the particle type.

5.2.4. Photolepton-hadron Processes

To be delivered.

5.2.5. Optical Photon Processes

A photon is considered to be *optical* when its wavelength is much greater than the typical atomic spacing. In GEANT4 optical photons are treated as a class of particle distinct from their higher energy *gamma* cousins. This implementation allows the wave-like properties of electromagnetic radiation to be incorporated into the optical photon process. Because this theoretical description breaks down at higher energies, there is no smooth transition as a function of energy between the optical photon and gamma particle classes.

For the simulation of optical photons to work correctly in GEANT4, they must be imputed a linear polarization. This is unlike most other particles in GEANT4 but is automatically and correctly done for optical photons that are generated as secondaries by existing processes in GEANT4. Not so, if the user wishes to start optical photons as primary particles. In this case, the user must set the linear polarization using particle gun methods, the General Particle Source, or his/her PrimaryGeneratorAction. For an unpolarized source, the linear polarization should be sampled randomly for each new primary photon.

The GEANT4 catalogue of processes at optical wavelengths includes refraction and reflection at medium boundaries, bulk absorption and Rayleigh scattering. Processes which produce optical photons include the Cerenkov effect, transition radiation and scintillation. Optical photons are generated in GEANT4 without energy conservation and their energy must therefore not be tallied as part of the energy balance of an event.

The optical properties of the medium which are key to the implementation of these types of processes are stored as entries in a `G4MaterialPropertiesTable` which is linked to the `G4Material` in question. These properties may be constants or they may be expressed as a function of the photon's wavelength. This table is

a private data member of the G4Material class. The G4MaterialPropertiesTable is implemented as a hash directory, in which each entry consists of a *value* and a *key*. The key is used to quickly and efficiently retrieve the corresponding value. All values in the dictionary are either instantiations of G4double or the class G4MaterialPropertyVector, and all keys are of type G4String.

A G4MaterialPropertyVector is composed of instantiations of the class G4MPVEntry. The G4MPVEntry is a pair of numbers, which in the case of an optical property, are the photon momentum and corresponding property value. The G4MaterialPropertyVector is implemented as a G4std::vector, with the sorting operation defined as $MPVEntry_1 < MPVEntry_2 == photon\_momentum_1 < photon\_momentum_2$. This results in all G4MaterialPropertyVectors being sorted in ascending order of photon momenta. It is possible for the user to add as many material (optical) properties to the material as he wishes using the methods supplied by the G4MaterialPropertiesTable class. An example of this is shown in Example 5.3.

Example 5.3. Optical properties added to a G4MaterialPropertiesTable and linked to a G4Material

```
const G4int NUMENTRIES = 32;

G4double ppckov[NUMENTRIES] = {2.034*eV, ......, 4.136*eV};
G4double rindex[NUMENTRIES] = {1.3435, ......, 1.3608};
G4double absorption[NUMENTRIES] = {344.8*cm, ......, 1450.0*cm];

G4MaterialPropertiesTable *MPT = new G4MaterialPropertiesTable();

MPT -> AddConstProperty("SCINTILLATIONYIELD",100./MeV);

MPT -> AddProperty("RINDEX",ppckov,rindex,NUMENTRIES};
MPT -> AddProperty("ABSLENGTH",ppckov,absorption,NUMENTRIES};

scintillator -> SetMaterialPropertiesTable(MPT);
```

5.2.5.1. Generation of Photons in processes/electromagnetic/xrays - Cerenkov Effect

The radiation of Cerenkov light occurs when a charged particle moves through a dispersive medium faster than the group velocity of light in that medium. Photons are emitted on the surface of a cone, whose opening angle with respect to the particle's instantaneous direction decreases as the particle slows down. At the same time, the frequency of the photons emitted increases, and the number produced decreases. When the particle velocity drops below the local speed of light, the radiation ceases and the emission cone angle collapses to zero. The photons produced by this process have an inherent polarization perpendicular to the cone's surface at production.

The flux, spectrum, polarization and emission of Cerenkov radiation in the AlongStepDoIt method of the class G4Cerenkov follow well-known formulae, with two inherent computational limitations. The first arises from step-wise simulation, and the second comes from the requirement that numerical integration calculate the average number of Cerenkov photons per step. The process makes use of a G4PhysicsTable which contains incremental integrals to expedite this calculation.

The time and position of Cerenkov photon emission are calculated from quantities known at the beginning of a charged particle's step. The step is assumed to be rectilinear even in the presence of a magnetic field. The user may limit the step size by specifying a maximum (average) number of Cerenkov photons created during the step, using the SetMaxNumPhotonsPerStep(const G4int NumPhotons) method. The actual number generated will necessarily be different due to the Poissonian nature of the production. In the present implementation, the production density of photons is distributed evenly along the particle's track segment, even if the particle has slowed significantly during the step.

The frequently very large number of secondaries produced in a single step (about 300/cm in water), compelled the idea in GEANT3.21 of suspending the primary particle until all its progeny have been tracked. Despite the fact that GEANT4 employs dynamic memory allocation and thus does not suffer from the limitations of GEANT3.21 with its fixed large initial ZEBRA store, GEANT4 nevertheless provides for an analogous functionality with the public method SetTrackSecondariesFirst. An example of the registration of the Cerenkov process is given in Example 5.4.

Example 5.4. Registration of the Cerenkov process in `PhysicsList`.

```
#include "G4Cerenkov.hh"

void ExptPhysicsList::ConstructOp(){

  G4Cerenkov*   theCerenkovProcess = new G4Cerenkov("Cerenkov");

  G4int MaxNumPhotons = 300;

  theCerenkovProcess->SetTrackSecondariesFirst(true);
  theCerenkovProcess->SetMaxNumPhotonsPerStep(MaxNumPhotons);

  theParticleIterator->reset();
  while( (*theParticleIterator)() ){
    G4ParticleDefinition* particle = theParticleIterator->value();
    G4ProcessManager* pmanager = particle->GetProcessManager();
    G4String particleName = particle->GetParticleName();
    if (theCerenkovProcess->IsApplicable(*particle)) {
      pmanager->AddContinuousProcess(theCerenkovProcess);
    }
  }
}
```

5.2.5.2. Generation of Photons in `processes/electromagnetic/xrays` - Scintillation

Every scintillating material has a characteristic light yield, `SCINTILLATIONYIELD`, and an intrinsic resolution, `RESOLUTIONSCALE`, which generally broadens the statistical distribution of generated photons. A wider intrinsic resolution is due to impurities which are typical for doped crystals like NaI(Tl) and CsI(Tl). On the other hand, the intrinsic resolution can also be narrower when the Fano factor plays a role. The actual number of emitted photons during a step fluctuates around the mean number of photons with a width given by `ResolutionScale*sqrt(MeanNumberOfPhotons)`. The average light yield, `MeanNumberOfPhotons`, has a linear dependence on the local energy deposition, but it may be different for minimum ionizing and non-minimum ionizing particles.

A scintillator is also characterized by its photon emission spectrum and by the exponential decay of its time spectrum. In GEANT4 the scintillator can have a fast and a slow component. The relative strength of the fast component as a fraction of total scintillation yield is given by the `YIELDRATIO`. Scintillation may be simulated by specifying these empirical parameters for each material. It is sufficient to specify in the user's `DetectorConstruction` class a relative spectral distribution as a function of photon energy for the scintillating material. An example of this is shown in Example 5.5

Example 5.5. Specification of scintillation properties in `DetectorConstruction`.

```
  const G4int NUMENTRIES = 9;
  G4double Scnt_PP[NUMENTRIES] = { 6.6*eV, 6.7*eV, 6.8*eV, 6.9*eV,
                                   7.0*eV, 7.1*eV, 7.2*eV, 7.3*eV, 7.4*eV };

  G4double Scnt_FAST[NUMENTRIES] = { 0.000134, 0.004432, 0.053991, 0.241971,
                                     0.398942, 0.000134, 0.004432, 0.053991,
                                     0.241971 };
  G4double Scnt_SLOW[NUMENTRIES] = { 0.000010, 0.000020, 0.000030, 0.004000,
                                     0.008000, 0.005000, 0.020000, 0.001000,
                                     0.000010 };

  G4Material* Scnt;
  G4MaterialPropertiesTable* Scnt_MPT = new G4MaterialPropertiesTable();

  Scnt_MPT->AddProperty("FASTCOMPONENT", Scnt_PP, Scnt_FAST, NUMENTRIES);
  Scnt_MPT->AddProperty("SLOWCOMPONENT", Scnt_PP, Scnt_SLOW, NUMENTRIES);

  Scnt_MPT->AddConstProperty("SCINTILLATIONYIELD", 5000./MeV);
  Scnt_MPT->AddConstProperty("RESOLUTIONSCALE", 2.0);
  Scnt_MPT->AddConstProperty("FASTTIMECONSTANT",  1.*ns);
  Scnt_MPT->AddConstProperty("SLOWTIMECONSTANT", 10.*ns);
  Scnt_MPT->AddConstProperty("YIELDRATIO", 0.8);

  Scnt->SetMaterialPropertiesTable(Scnt_MPT);
```

In cases where the scintillation yield of a scintillator depends on the particle type, different scintillation processes may be defined for them. How this yield scales to the one specified for the material is expressed with the `ScintillationYieldFactor` in the user's `PhysicsList` as shown in Example 5.6. In those cases where the fast to slow excitation ratio changes with particle type, the method `SetScintillationExcitationRatio` can be called for each scintillation process (see the advanced underground_physics example). This overwrites the `YieldRatio` obtained from the `G4MaterialPropertiesTable`.

Example 5.6. Implementation of the scintillation process in `PhysicsList`.

```
G4Scintillation* theMuonScintProcess = new G4Scintillation("Scintillation");

theMuonScintProcess->SetTrackSecondariesFirst(true);
theMuonScintProcess->SetScintillationYieldFactor(0.8);

theParticleIterator->reset();
while( (*theParticleIterator)() ){
  G4ParticleDefinition* particle = theParticleIterator->value();
  G4ProcessManager* pmanager = particle->GetProcessManager();
  G4String particleName = particle->GetParticleName();
  if (theMuonScintProcess->IsApplicable(*particle)) {
     if (particleName == "mu+") {
        pmanager->AddProcess(theMuonScintProcess);
        pmanager->SetProcessOrderingToLast(theMuonScintProcess, idxAtRest);
        pmanager->SetProcessOrderingToLast(theMuonScintProcess, idxPostStep);
     }
  }
}
```

A Gaussian-distributed number of photons is generated according to the energy lost during the step. A resolution scale of 1.0 produces a statistical fluctuation around the average yield set with `AddConstProperty("SCINTILLATIONYIELD")`, while values > 1 broaden the fluctuation. A value of zero produces no fluctuation. Each photon's frequency is sampled from the empirical spectrum. The photons originate evenly along the track segment and are emitted uniformly into 4# with a random linear polarization and at times characteristic for the scintillation component.

5.2.5.3. Generation of Photons in `processes/optical` - Wavelength Shifting

Wavelength Shifting (WLS) fibers are used in many high-energy particle physics experiments. They absorb light at one wavelength and re-emit light at a different wavelength and are used for several reasons. For one, they tend to decrease the self-absorption of the detector so that as much light reaches the PMTs as possible. WLS fibers are also used to match the emission spectrum of the detector with the input spectrum of the PMT.

A WLS material is characterized by its photon absorption and photon emission spectrum and by a possible time delay between the absorption and re-emission of the photon. Wavelength Shifting may be simulated by specifying these empirical parameters for each WLS material in the simulation. It is sufficient to specify in the user's `DetectorConstruction` class a relative spectral distribution as a function of photon energy for the WLS material. WLSABSLENGTH is the absorption length of the material as a function of the photon's momentum. WLSCOMPONENT is the relative emission spectrum of the material as a function of the photon's momentum, and WLSTIMECONSTANT accounts for any time delay which may occur between absorption and re-emission of the photon. An example is shown in Example 5.7.

Example 5.7. Specification of WLS properties in `DetectorConstruction`.

```
const G4int nEntries = 9;

G4double PhotonEnergy[nEntries] = { 6.6*eV, 6.7*eV, 6.8*eV, 6.9*eV,
                                    7.0*eV, 7.1*eV, 7.2*eV, 7.3*eV, 7.4*eV };

G4double RIndexFiber[nEntries] =
          { 1.60, 1.60, 1.60, 1.60, 1.60, 1.60, 1.60, 1.60, 1.60 };
G4double AbsFiber[nEntries] =
          {0.1*mm,0.2*mm,0.3*mm,0.4*cm,1.0*cm,10*cm,1.0*m,10.0*m,10.0*m};
G4double EmissionFiber[nEntries] =
          {0.0, 0.0, 0.0, 0.1, 0.5, 1.0, 5.0, 10.0, 10.0 };

 G4Material* WLSFiber;
 G4MaterialPropertiesTable* MPTFiber = new G4MaterialPropertiesTable();

 MPTFiber->AddProperty("RINDEX",PhotonEnergy,RIndexFiber,nEntries);
 MPTFiber->AddProperty("WLSABSLENGTH",PhotonEnergy,AbsFiber,nEntries);
 MPTFiber->AddProperty("WLSCOMPONENT",PhotonEnergy,EmissionFiber,nEntries);
 MPTFiber->AddConstProperty("WLSTIMECONSTANT", 0.5*ns);

 WLSFiber->SetMaterialPropertiesTable(MPTFiber);
```

The process is defined in the PhysicsList in the usual way. The process class name is G4OpWLS. It should be instantiated with theWLSProcess = new G4OpWLS("OpWLS") and attached to the process manager of the optical photon as a DiscreteProcess. The way the WLSTIMECONSTANT is used depends on the time profile method chosen by the user. If in the PhysicsList theWLSProcess->UseTimeGenerator("exponential") option is set, the time delay between absorption and re-emission of the photon is sampled from an exponential distribution, with the decay term equal to WLSTIMECONSTANT. If, on the other hand, theWLSProcess->UseTimeGenerator("delta") is chosen, the time delay is a delta function and equal to WLSTIMECONSTANT. The default is "delta" in case the G4OpWLS::UseTimeGenerator(const G4String name) method is not used.

5.2.5.4. Tracking of Photons in `processes/optical`

Absorption

The implementation of optical photon bulk absorption, `G4OpAbsorption`, is trivial in that the process merely kills the particle. The procedure requires the user to fill the relevant `G4MaterialPropertiesTable` with empirical data for the absorption length, using `ABSLENGTH` as the property key in the public method `AddProperty`. The absorption length is the average distance traveled by a photon before being absorpted by the medium; i.e. it is the mean free path returned by the `GetMeanFreePath` method.

Rayleigh Scattering

The differential cross section in Rayleigh scattering, #/#, is proportional to $\cos^2$(#), where # is the polar of the new polarization vector with respect to the old polarization vector. The `G4OpRayleigh` scattering process samples this angle accordingly and then calculates the scattered photon's new direction by requiring that it be perpendicular to the photon's new polarization in such a way that the final direction, initial and final polarizations are all in one plane. This process thus depends on the particle's polarization (spin). The photon's polarization is a data member of the `G4DynamicParticle` class.

A photon which is not assigned a polarization at production, either via the `SetPolarization` method of the `G4PrimaryParticle` class, or indirectly with the `SetParticlePolarization` method of the `G4ParticleGun` class, may not be Rayleigh scattered. Optical photons produced by the `G4Cerenkov` process have inherently a polarization perpendicular to the cone's surface at production. Scintillation photons have a random linear polarization perpendicular to their direction.

The process requires a `G4MaterialPropertiesTable` to be filled by the user with Rayleigh scattering length data. The Rayleigh scattering attenuation length is the average distance traveled by a photon before it is Rayleigh scattered in the medium and it is the distance returned by the `GetMeanFreePath` method. The `G4OpRayleigh` class provides a `RayleighAttenuationLengthGenerator` method which calculates the attenuation coef-

ficient of a medium following the Einstein-Smoluchowski formula whose derivation requires the use of statistical mechanics, includes temperature, and depends on the isothermal compressibility of the medium. This generator is convenient when the Rayleigh attenuation length is not known from measurement but may be calculated from first principles using the above material constants. For a medium named *Water* and no Rayleigh scattering attenutation length specified by the user, the program automatically calls the `RayleighAttenuationLengthGenerator` which calculates it for 10 degrees Celsius liquid water.

Boundary Process

Reference: E. Hecht and A. Zajac, Optics [Hecht1974]

For the simple case of a perfectly smooth interface between two dielectric materials, all the user needs to provide are the refractive indices of the two materials stored in their respective `G4MaterialPropertiesTable`. In all other cases, the optical boundary process design relies on the concept of *surfaces*. The information is split into two classes. One class in the material category keeps information about the physical properties of the surface itself, and a second class in the geometry category holds pointers to the relevant physical and logical volumes involved and has an association to the physical class. Surface objects of the second type are stored in a related table and can be retrieved by either specifying the two ordered pairs of physical volumes touching at the surface, or by the logical volume entirely surrounded by this surface. The former is called a *border surface* while the latter is referred to as the *skin surface*. This second type of surface is useful in situations where a volume is coded with a reflector and is placed into many different mother volumes. A limitation is that the skin surface can only have one and the same optical property for all of the enclosed volume's sides. The border surface is an ordered pair of physical volumes, so in principle, the user can choose different optical properties for photons arriving from the reverse side of the same interface. For the optical boundary process to use a border surface, the two volumes must have been positioned with `G4PVPlacement`. The ordered combination can exist at many places in the simulation. When the surface concept is not needed, and a perfectly smooth surface exists beteen two dielectic materials, the only relevant property is the index of refraction, a quantity stored with the material, and no restriction exists on how the volumes were positioned.

The physical surface object also specifies which model the boundary process should use to simulate interactions with that surface. In addition, the physical surface can have a material property table all its own. The usage of this table allows all specular constants to be wavelength dependent. In case the surface is painted or wrapped (but not a cladding), the table may include the thin layer's index of refraction. This allows the simulation of boundary effects at the intersection between the medium and the surface layer, as well as the Lambertian reflection at the far side of the thin layer. This occurs within the process itself and does not invoke the `G4Navigator`. Combinations of surface finish properties, such as *polished* or *ground* and *front painted* or *back painted*, enumerate the different situations which can be simulated.

When a photon arrives at a medium boundary its behavior depends on the nature of the two materials that join at that boundary. Medium boundaries may be formed between two dielectric materials or a dielectric and a metal. In the case of two dielectric materials, the photon can undergo total internal reflection, refraction or reflection, depending on the photon's wavelength, angle of incidence, and the refractive indices on both sides of the boundary. Furthermore, reflection and transmission probabilites are sensitive to the state of linear polarization. In the case of an interface between a dielectric and a metal, the photon can be absorbed by the metal or reflected back into the dielectric. If the photon is absorbed it can be detected according to the photoelectron efficiency of the metal.

As expressed in Maxwell's equations, Fresnel reflection and refraction are intertwined through their relative probabilities of occurrence. Therefore neither of these processes, nor total internal reflection, are viewed as individual processes deserving separate class implementation. Nonetheless, an attempt was made to adhere to the abstraction of having independent processes by splitting the code into different methods where practicable.

One implementation of the `G4OpBoundaryProcess` class employs the UNIFIED model [A. Levin and C. Moisan, A More Physical Approach to Model the Surface Treatment of Scintillation Counters and its Implementation into DETECT, TRIUMF Preprint TRI-PP-96-64, Oct. 1996] of the DETECT program [G.F. Knoll, T.F. Knoll and T.M. Henderson, Light Collection Scintillation Detector Composites for Neutron Detection, IEEE Trans. Nucl. Sci., 35 (1988) 872.]. It applies to dielectric-dielectric interfaces and tries to provide a realistic simulation, which deals with all aspects of surface finish and reflector coating. The surface may be assumed as smooth and covered with a metallized coating representing a specular reflector with given reflection coefficient, or painted

with a diffuse reflecting material where Lambertian reflection occurs. The surfaces may or may not be in optical contact with another component and most importantly, one may consider a surface to be made up of micro-facets with normal vectors that follow given distributions around the nominal normal for the volume at the impact point. For very rough surfaces, it is possible for the photon to inversely aim at the same surface again after reflection of refraction and so multiple interactions with the boundary are possible within the process itself and without the need for relocation by `G4Navigator`.

The UNIFIED model provides for a range of different reflection mechanisms. The specular lobe constant represents the reflection probability about the normal of a micro facet. The specular spike constant, in turn, illustrates the probability of reflection about the average surface normal. The diffuse lobe constant is for the probability of internal Lambertian reflection, and finally the back-scatter spike constant is for the case of several reflections within a deep groove with the ultimate result of exact back-scattering. The four probabilities must add up to one, with the diffuse lobe constant being implicit. The reader may consult the reference for a thorough description of the model.

Example 5.8. Dielectric-dielectric surface properties defined via the *G4OpticalSurface*.

```
G4VPhysicalVolume* volume1;
G4VPhysicalVolume* volume2;

G4OpticalSurface* OpSurface = new G4OpticalSurface("name");

G4LogicalBorderSurface* Surface = new
  G4LogicalBorderSurface("name",volume1,volume2,OpSurface);

G4double sigma_alpha = 0.1;

OpSurface -> SetType(dielectric_dielectric);
OpSurface -> SetModel(unified);
OpSurface -> SetFinish(groundbackpainted);
OpSurface -> SetSigmaAlpha(sigma_alpha);

const G4int NUM = 2;

G4double pp[NUM] = {2.038*eV, 4.144*eV};
G4double specularlobe[NUM] = {0.3, 0.3};
G4double specularspike[NUM] = {0.2, 0.2};
G4double backscatter[NUM] = {0.1, 0.1};
G4double rindex[NUM] = {1.35, 1.40};
G4double reflectivity[NUM] = {0.3, 0.5};
G4double efficiency[NUM] = {0.8, 0.1};

G4MaterialPropertiesTable* SMPT = new G4MaterialPropertiesTable();

SMPT -> AddProperty("RINDEX",pp,rindex,NUM);
SMPT -> AddProperty("SPECULARLOBECONSTANT",pp,specularlobe,NUM);
SMPT -> AddProperty("SPECULARSPIKECONSTANT",pp,specularspike,NUM);
SMPT -> AddProperty("BACKSCATTERCONSTANT",pp,backscatter,NUM);
SMPT -> AddProperty("REFLECTIVITY",pp,reflectivity,NUM);
SMPT -> AddProperty("EFFICIENCY",pp,efficiency,NUM);

OpSurface -> SetMaterialPropertiesTable(SMPT);
```

The original GEANT3.21 implementation of this process is also available via the GLISUR methods flag. [GEANT Detector Description and Simulation Tool, Application Software Group, Computing and Networks Division, CERN, PHYS260-6 tp 260-7.].

Example 5.9. Dielectric metal surface properties defined via the *G4OpticalSurface*.

```
G4LogicalVolume* volume_log;

G4OpticalSurface* OpSurface = new G4OpticalSurface("name");

G4LogicalSkinSurface* Surface = new
  G4LogicalSkinSurface("name",volume_log,OpSurface);

OpSurface -> SetType(dielectric_metal);
OpSurface -> SetFinish(ground);
OpSurface -> SetModel(glisur);

G4double polish = 0.8;

G4MaterialPropertiesTable *OpSurfaceProperty = new G4MaterialPropertiesTable();

OpSurfaceProperty -> AddProperty("REFLECTIVITY",pp,reflectivity,NUM);
OpSurfaceProperty -> AddProperty("EFFICIENCY",pp,efficiency,NUM);

OpSurface -> SetMaterialPropertiesTable(OpSurfaceProperty);
```

The reflectivity off a metal surface can also be calculated by way of a complex index of refraction. Instead of storing the REFLECTIVITY directly, the user stores the real part (REALRINDEX) and the imaginary part (IMAGINARYRINDEX) as a function of photon energy separately in the G4MaterialPropertyTable. Geant4 then calculates the reflectivity depending on the incident angle, photon energy, degree of TE and TM polarization, and this complex refractive index.

The program defaults to the GLISUR model and *polished* surface finish when no specific model and surface finish is specified by the user. In the case of a dielectric-metal interface, or when the GLISUR model is specified, the only surface finish options available are *polished* or *ground*. For dielectric-metal surfaces, the `G4OpBoundaryProcess` also defaults to unit reflectivity and zero detection efficiency. In cases where the user specifies the UNIFIED model, but does not otherwise specify the model reflection probability constants, the default becomes Lambertian reflection.

Martin Janecek and Bill Moses (Lawrence Berkeley National Laboratory) built an instrument for measuring the angular reflectivity distribution inside of BGO crystals with common surface treatments and reflectors applied. These results have been incorporate into the Geant4 code. A third class of reflection type besides dielectric_metal and dielectric_dielectric is added: dielectric_LUT. The distributions have been converted to 21 look-up-tables (LUT); so far for 1 scintillator material (BGO) x 3 surface treatments x 7 reflector materials. The modified code allows the user to specify the surface treatment (rough-cut, chemically etched, or mechanically polished), the attached reflector (Lumirror, Teflon, ESR film, Tyvek, or TiO2 paint), and the bonding type (air-coupled or glued). The glue used is MeltMount, and the ESR film used is VM2000. Each LUT consists of measured angular distributions with 4º by 5º resolution in theta and phi, respectively, for incidence angles from 0º to 90º degrees, in 1º-steps. The code might in the future be updated by adding more LUTs, for instance, for other scintillating materials (such as LSO or NaI). To use these LUT the user has to download them from Geant4 Software Download and set an environment variable, `G4REALSURFACEDATA`, to the directory of `geant4/data/RealSurface1.0`. For details see: M. Janecek, W. Moses IEEE Transactions on Nuclear Science .

The enumeration G4OpticalSurfaceFinish has been extended to include (what follows should be a 2 column table):

```
  polishedlumirrorair,         // mechanically polished surface, with lumirror
  polishedlumirrorglue,        // mechanically polished surface, with lumirror & meltmount
  polishedair,                 // mechanically polished surface
  polishedteflonair,           // mechanically polished surface, with teflon
  polishedtioair,              // mechanically polished surface, with tio paint
  polishedtyvekair,            // mechanically polished surface, with tyvek
  polishedvm2000air,           // mechanically polished surface, with esr film
  polishedvm2000glue,          // mechanically polished surface, with esr film & meltmount
  etchedlumirrorair,           // chemically etched surface, with lumirror
  etchedlumirrorglue,          // chemically etched surface, with lumirror & meltmount
  etchedair,                   // chemically etched surface
  etchedteflonair,             // chemically etched surface, with teflon
  etchedtioair,                // chemically etched surface, with tio paint
  etchedtyvekair,              // chemically etched surface, with tyvek
  etchedvm2000air,             // chemically etched surface, with esr film
```

```
  etchedvm2000glue,           // chemically etched surface, with esr film & meltmount
  groundlumirrorair,          // rough-cut surface, with lumirror
  groundlumirrorglue,         // rough-cut surface, with lumirror & meltmount
  groundair,                  // rough-cut surface
  groundteflonair,            // rough-cut surface, with teflon
  groundtioair,               // rough-cut surface, with tio paint
  groundtyvekair,             // rough-cut surface, with tyvek
  groundvm2000air,            // rough-cut surface, with esr film
  groundvm2000glue            // rough-cut surface, with esr film & meltmount
```

To use a look-up-table, all the user needs to specify for an `G4OpticalSurface` is: `SetType(dielectric_LUT)`, `SetModel(LUT)` and for example, `SetFinish(polishedtyvekair)`.

5.2.6. Parameterization

In this section we describe how to use the parameterization or "fast simulation" facilities of GEANT4. Examples are provided in the **examples/novice/N05 directory**.

5.2.6.1. Generalities:

The Geant4 parameterization facilities allow you to shortcut the detailed tracking in a given volume and for given particle types in order for you to provide your own implementation of the physics and of the detector response.

Parameterisations are bound to a **`G4Region`** object, which, in the case of fast simulation is also called an **envelope**. Prior to release 8.0, parameterisations were bound to a `G4LogicalVolume`, the root of a volume hierarchy. These root volumes are now attributes of the `G4Region`. Envelopes often correspond to the volumes of sub-detectors: electromagnetic calorimeters, tracking chambers, etc. With GEANT4 it is also possible to define envelopes by overlaying a parallel or "ghost" geometry as discussed in Section 5.2.6.7.

In GEANT4, parameterisations have three main features. You must specify:

- the particle types for which your parameterisation is valid;
- the dynamics conditions for which your parameterisation is valid and must be triggered;
- the parameterisation itself: where the primary will be killed or moved, whether or not to create it or create secondaries, etc., and where the detector response will be computed.

GEANT4 will message your parameterisation code for each step starting in any root G4LogicalVolume (including daughters. sub-daughters, etc. of this volume) of the `G4Region`. It will proceed by first asking the available parameterisations for the current particle type if one of them (and only one) wants to issue a trigger. If so it will invoke its parameterisation. In this case, the tracking **will not apply physics** to the particle in the step. Instead, the UserSteppingAction will be invoked.

Parameterisations look like a "user stepping action" but are more advanced because:

- parameterisation code is messaged only in the `G4Region` to which it is bound;
- parameterisation code is messaged anywhere in the `G4Region`, that is, any volume in which the track is located;
- GEANT4 will provide information to your parameterisation code about the current root volume of the `G4Region` in which the track is travelling.

5.2.6.2. Overview of Parameterisation Components

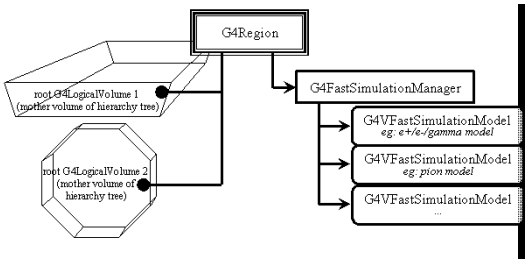
The GEANT4 components which allow the implementation and control of parameterisations are:

`G4VFastSimulationModel`
: This is the abstract class for the implementation of parameterisations. You must inherit from it to implement your concrete parameterisation model.

`G4FastSimulationManager`
: The G4VFastSimulationModel objects are attached to the `G4Region` through a G4FastSimulationManager. This object will manage the list of models and will message them at tracking time.

`G4Region/Envelope`
As mentioned before, an envelope in GEANT4 is a **`G4Region`**. The parameterisation is bound to the `G4Region` by setting a `G4FastSimulationManager` pointer to it.

The figure below shows how the `G4VFastSimulationModel` and `G4FastSimulationManager` objects are bound to the `G4Region`. Then for all root G4LogicalVolume's held by the G4Region, the fast simulation code is active.



`G4FastSimulationManagerProcess`
This is a `G4VProcess`. It provides the interface between the tracking and the parameterisation. It must be set in the process list of the particles you want to parameterise.

`G4GlobalFastSimulationManager`
This a singleton class which provides the management of the `G4FastSimulationManager` objects and some ghost facilities.

5.2.6.3. The `G4VFastSimulationModel` Abstract Class

Constructors:

The `G4VFastSimulationModel` class has two constructors. The second one allows you to get started quickly:

`G4VFastSimulationModel( const G4String& aName)`:
Here `aName` identifies the parameterisation model.

`G4VFastSimulationModel(const G4String& aName, G4Region*, G4bool IsUnique=false):`
In addition to the model name, this constructor accepts a G4Region pointer. The needed G4FastSimulationManager object is constructed if necessary, passing to it the G4Region pointer and the boolean value. If it already exists, the model is simply added to this manager. Note that the *G4VFastSimulationModel object will not keep track of the G4Region passed in the constructor*. The boolean argument is there for optimization purposes: if you know that the G4Region has a unique root G4LogicalVolume, uniquely placed, you can set the boolean value to "true".

Virtual methods:

The G4VFastSimulationModel has three pure virtual methods which must be overriden in your concrete class:

`G4VFastSimulationModel( const G4String& aName):`
Here aName identifies the parameterisation model.

`G4bool ModelTrigger( const G4FastTrack&):`
You must return "true" when the dynamic conditions to trigger your parameterisation are fulfilled. G4FastTrack provides access to the current G4Track, gives simple access to the current root G4LogicalVolume related features (its G4VSolid, and G4AffineTransform references between the global and the root G4LogicalVolume local coordinates systems) and simple access to the position and momentum expressed in the root G4LogicalVolume coordinate system. Using these quantities and the G4VSolid methods, you can for example easily check how far you are from the root G4LogicalVolume boundary.

`G4bool IsApplicable( const G4ParticleDefinition&):`
In your implementation, you must return "true" when your model is applicable to the G4ParticleDefinition passed to this method. The G4ParticleDefinition provides all intrinsic particle information (mass, charge, spin, name ...).

If you want to implement a model which is valid only for certain particle types, it is recommended for efficiency that you use the static pointer of the corresponding particle classes.

As an example, in a model valid for *gamma*s only, the IsApplicable() method should take the form:

```
#include "G4Gamma.hh"

G4bool MyGammaModel::IsApplicable(const G4ParticleDefinition& partDef)
{
  return &partDef == G4Gamma::GammaDefinition();
}
```

`G4bool ModelTrigger( const G4FastTrack&):`
You must return "true" when the dynamic conditions to trigger your parameterisation are fulfilled. The G4FastTrack provides access to the current G4Track, gives simple access to envelope related features (G4LogicalVolume, G4VSolid, and G4AffineTransform references between the global and the envelope local coordinates systems) and simple access to the position and momentum expressed in the envelope coordinate system. Using these quantities and the G4VSolid methods, you can for example easily check how far you are from the envelope boundary.

`void DoIt( const G4FastTrack&, G4FastStep&):`
The details of your parameterisation will be implemented in this method. The G4FastTrack reference provides the input information, and the final state of the particles after parameterisation must be returned through the G4FastStep reference. Tracking for the final state particles is requested after your parameterisation has been invoked.

5.2.6.4. The `G4FastSimulationManager` Class:

G4FastSimulationManager functionnalities regarding the use of ghost volumes are explained in Section 5.2.6.7.

Constructor:

`G4FastSimulationManager( G4Region *anEnvelope, G4bool IsUnique=false):`
This is the only constructor. You specify the G4Region by providing its pointer. The G4FastSimulationManager object will bind itself to this G4Region. If you know that this G4Region has a single root G4LogicalVolume, placed only once, you can set the IsUnique boolean to "true" to allow some optimization.

Note that if you choose to use the G4VFastSimulationModel(const G4String&, G4Region*, G4bool) constructor for your model, the G4FastSimulationManager will be constructed using the given G4Region* and G4bool values of the model constructor.

G4VFastSimulationModel object management:

The following two methods provide the usual management functions.

- **`void AddFastSimulationModel( G4VFastSimulationModel*)`**
- **`RemoveFastSimulationModel( G4VFastSimulationModel*)`**

Interface with the G4FastSimulationManagerProcess:

This is described in the User's Guide for Toolkit Developers (section 3.9.6)

5.2.6.5. The `G4FastSimulationManagerProcess` Class

This G4VProcess serves as an interface between the tracking and the parameterisation. At tracking time, it collaborates with the G4FastSimulationManager of the current volume, if any, to allow the models to trigger. If no manager exists or if no model issues a trigger, the tracking goes on normally.

In the present implementation, you must set this process in the G4ProcessManager of the particles you parameterise to enable your parameterisation.

The processes ordering is:

```
   [n-3] ...
   [n-2] Multiple Scattering
   [n-1] G4FastSimulationManagerProcess
   [ n ] G4Transportation
```

This ordering is important if you use ghost geometries, since the G4FastSimulationManagerProcess will provide navigation in the ghost world to limit the step on ghost boundaries.

The G4FastSimulationManager must be added to the process list of a particle as a continuous and discrete process if you use ghost geometries for this particle. You can add it as a discrete process if you don't use ghosts.

The following code registers the G4FastSimulationManagerProcess with all the particles as a discrete and continuous process:

```
void MyPhysicsList::addParameterisation()
{
  G4FastSimulationManagerProcess*
    theFastSimulationManagerProcess = new G4FastSimulationManagerProcess();
  theParticleIterator->reset();
  while( (*theParticleIterator)() )
    {
      G4ParticleDefinition* particle = theParticleIterator->value();
      G4ProcessManager* pmanager = particle->GetProcessManager();
      pmanager->AddProcess(theFastSimulationManagerProcess, -1, 0, 0);
    }
}
```

5.2.6.6. The `G4GlobalFastSimulationManager` Singleton Class

This class is a singleton which can be accessed as follows:

```
#include "G4GlobalFastSimulationManager.hh"
...
...
G4GlobalFastSimulationManager* globalFSM;
globalFSM = G4GlobalFastSimulationManager::getGlobalFastSimulationManager();
...
...
```

Presently, you will mainly need to use the GlobalFastSimulationManager if you use ghost geometries.

5.2.6.7. Parameterisation Using Ghost Geometries

In some cases, volumes of the tracking geometry do not allow envelopes to be defined. This may be the case with a geometry coming from a CAD system. Since such a geometry is flat, a parallel geometry must be used to define the envelopes.

Another interesting case involves defining an envelope which groups the electromagnetic and hadronic calorimeters of a detector into one volume. This may be useful when parameterizing the interaction of charged pions. You will very likely not want electrons to see this envelope, which means that ghost geometries have to be organized by particle flavours.

Using ghost geometries implies some more overhead in the parameterisation mechanism for the particles sensitive to ghosts, since navigation is provided in the ghost geometry by the G4FastSimulationManagerProcess. Usually,

however, only a few volumes will be placed in this ghost world, so that the geometry computations will remain rather cheap.

In the existing implementation (temporary implementation with G4Region but before parallel geometry implementation), you may only consider ghost G4Regions with just one root G4LogicalVolume. The G4GlobalFastSimulationManager provides the construction of the ghost geometry by making first an empty "clone" of the world for tracking provided by the construct() method of your G4VUserDetectorConstruction concrete class. You provide the placement of the G4Region root G4LogicalVolume relative to the ghost world coordinates in the G4FastSimulationManager objects. A ghost G4Region is recognized by the fact that its associated G4FastSimulationManager retains a non-empty list of placements.

The G4GlobalFastSimulationManager will then use both those placements and the IsApplicable() methods of the models attached to the G4FastSimulationManager objects to build the flavour-dependant ghost geometries.

Then at the beginning of the tracking of a particle, the appropriate ghost world, if any, will be selected.

The steps required to build one ghost G4Region are:

1. built the ghost G4Region : myGhostRegion;
2. build the root G4LogicalVolume: myGhostLogical, set it to myGhostRegion;
3. build a G4FastSimulationManager object, myGhostFSManager, giving myGhostRegion as argument of the constructor;
4. give to the G4FastSimulationManager the placement of the myGhostLogical, by invoking for the G4FastSimulationManager method:

   ```
   AddGhostPlacement(G4RotationMatrix*, const G4ThreeVector&);
   ```

   or:

   ```
   AddGhostPlacement(G4Transform3D*);
   ```

   where the rotation matrix and translation vector of the 3-D transformation describe the placement relative to the ghost world coordinates.
5. build your G4VFastSimulationModel objects and add them to the myGhostFSManager. *The IsApplicable() methods of your models will be used by the G4GlobalFastSimulationManager to build the ghost geometries corresponding to a given particle type.*
6. Invoke the G4GlobalFastSimulationManager method:

   ```
   G4GlobalFastSimulationManager::getGlobalFastSimulationManager()->
        CloseFastSimulation();
   ```

This last call will cause the G4GlobalFastSimulationManager to build the flavour-dependent ghost geometries. This call must be done before the RunManager closes the geometry. (It is foreseen that the run manager in the future will invoke the CloseFastSimulation() to synchronize properly with the closing of the geometry).

Visualization facilities are provided for ghosts geometries. After the CloseFastSimulation() invocation, it is possible to ask for the drawing of ghosts in an interactive session. The basic commands are:

- /vis/draw/Ghosts particle_name

  which makes the drawing of the ghost geometry associated with the particle specified by name in the command line.
- /vis/draw/Ghosts

  which draws all the ghost geometries.

5.2.6.8. Gflash Parameterization

This section describes how to use the Gflash library. Gflash is a concrete parameterization which is based on the equations and parameters of the original Gflash package from H1(hep-ex/0001020, Grindhammer & Peters, see physics manual) and uses the "fast simulation" facilities of GEANT4 described above. Briefly, whenever a e-/e+ particle enters the calorimeter, it is parameterized if it has a minimum energy and the shower is expected to be contained in the calorimeter (or " parameterization envelope"). If this is fulfilled the particle is killed, as well as all secondaries, and the energy is deposited according to the Gflash equations. An example, provided in **examples/extended/parametrisation/gflash/**, shows how to interface Gflash to your application. The simulation time is measured, so the user can immediately see the speed increase resulting from the use of Gflash.

5.2.6.9. Using the Gflash Parameterisation

To use Gflash "out of the box" the following steps are necessary:

- The user must add the fast simulation process to his process manager:

```
void MyPhysicsList::addParameterisation()
{
  G4FastSimulationManagerProcess*
    theFastSimulationManagerProcess = new G4FastSimulationManagerProcess();
  theParticleIterator->reset();
  while( (*theParticleIterator)() )
    {
      G4ParticleDefinition* particle = theParticleIterator->value();
      G4ProcessManager* pmanager = particle->GetProcessManager();
      pmanager->AddProcess(theFastSimulationManagerProcess, -1, 0, 0);
    }
}
```

- The envelope in which the parameterization should be performed must be specified (below: G4Region m_calo_region) and the GFlashShowerModel must be assigned to this region. Furthermore, the classes GFlashParticleBounds (which provides thresholds for the parameterization like minimal energy etc.), GflashHitMaker(a helper class to generate hits in the sensitive detector) and GFlashHomoShowerParamterisation (which does the computations) must be constructed (by the user at the moment) and assigned to the GFlashShowerModel. Please note that at the moment only homogeneous calorimeters are supported.

```
m_theFastShowerModel = new GFlashShowerModel("fastShowerModel",m_calo_region);
m_theParametrisation = new GFlashHomoShowerParamterisation(matManager->getMaterial(mat));
m_theParticleBounds  = new GFlashParticleBounds();
m_theHMaker          = new GFlashHitMaker();
m_theFastShowerModel->SetParametrisation(*m_theParametrisation);
m_theFastShowerModel->SetParticleBounds(*m_theParticleBounds) ;
m_theFastShowerModel->SetHitMaker(*m_theHMaker);
```

  The user must also set the material of the calorimeter, since the computation depends on the material.
- It is mandatory to use G4VGFlashSensitiveDetector as (additional) base class for the sensitive detector.

```
class ExGflashSensitiveDetector: public G4VSensitiveDetector ,public G4VGFlashSensitiveDetector
```

  Here it is necessary to implement a separate interface, where the GFlash spots are processed.

```
(ProcessHits(G4GFlashSpot*aSpot ,G4TouchableHistory* ROhist))
```

  A separate interface is used, because the Gflash spots naturally contain less information than the full simulation.

Since the parameters in the Gflash package are taken from fits to full simulations with Geant3, some retuning might be necessary for good agreement with Geant4 showers. For experiment-specific geometries some retuning might be necessary anyway. The tuning is quite complicated since there are many parameters (some correlated)

and cannot be described here (see again hep-ex/0001020). For brave users the Gflash framework already forsees the possibility of passing a class with the (users) parameters,**GVFlashHomoShowerTuning**, to the GFlashHomoShowerParamterisation constructor. The default parameters are the original Gflash parameters:

```
GFlashHomoShowerParameterisation(G4Material * aMat, GVFlashHomoShowerTuning * aPar = 0);
```

Now there is also a preliminary implemenation of a parameterization for sampling calorimeters.

The user must specify the active and passive material, as well as the thickness of the active and passive layer.

The sampling structure of the calorimeter is taken into account by using an "effective medium" to compute the shower shape.

All material properties needed are calculated automatically. If tuning is required, the user can pass his own parameter set in the class **GFlashSamplingShowerTuning**. Here the user can also set his calorimeter resolution.

All in all the constructor looks the following:

```
GFlashSamplingShowerParamterisation(G4Material * Mat1, G4Material * Mat2,G4double d1,G4double d2,
GVFlashSamplingShowerTuning * aPar = 0);
```

An implementation of some tools that should help the user to tune the parameterization is forseen.

5.2.7. Transportation Process

To be delivered by J. Apostolakis (<John.Apostolakis@cern.ch>).

5.3. Particles

5.3.1. Basic concepts

There are three levels of classes to describe particles in Geant4.

G4ParticleDefinition
: defines a particle

G4DynamicParticle
: describes a particle interacting with materials

G4Track
: describes a particle traveling in space and time

G4ParticleDefinition aggregates information to characterize a particle's properties, such as name, mass, spin, life time, and decay modes. *G4DynamicParticle* aggregates information to describe the dynamics of particles, such as energy, momentum, polarization, and proper time, as well as ``particle definition" information. *G4Track* includes all information necessary for tracking in a detector simulation, such as time, position, and step, as well as ``dynamic particle" information.

G4Track has all the information necessary for tracking in Geant4. It includes position, time, and step, as well as kinematics. Details of *G4Track* will be described in Section 5.1.

5.3.2. Definition of a particle

There are a large number of elementary particles and nuclei. Geant4 provides the *G4ParticleDefinition* class to represent particles, and various particles, such as the electron, proton, and gamma have their own classes derived from *G4ParticleDefinition*.

We do not need to make a class in Geant4 for every kind of particle in the world. There are more than 100 types of particles defined in Geant4 by default. Which particles should be included, and how to implement them, is determined according to the following criteria. (Of course, the user can define any particles he wants. Please see the **User's Guide: For ToolKit Developers**).

5.3.2.1. Particle List in Geant4

This list includes all particles in Geant4 and you can see properties of particles such as

- PDG encoding
- mass and width
- electric charge
- spin, isospin and parity
- magnetic moment
- quark contents
- life time and decay modes

Here is a list of particles in Geant4. This list is generated automatically by using Geant4 functionality, so listed values are same as those in your Geant4 application (as far as you do not change source codes).

Categories

- gluon / quarks / di-quarks
- leptons
- mesons
- baryons
- ions
- others

5.3.2.2. Classification of particles

1. elementary particles which should be tracked in Geant4 volumes

   All particles that can fly a finite length and interact with materials in detectors are included in this category. In addition, some particles with a very short lifetime are included for user's convenience.
   a. stable particles

      Stable means that the particle can not decay, or has a very small possibility to decay in detectors, e.g., gamma, electron, proton, and neutron.
   b. long life (>10^{-14}sec) particles

      Particles which may travel a finite length, e.g., muon, charged pions.
   c. short life particles that decay immediately in Geant4

      For example, pi^0, eta
   d. K^0 system

      K^0 "decays" immediately into K^0_S or K^0_L, and then K^0_S/ K^0_L decays according to its life time and decay modes.
   e. optical photon

      Gamma and optical photon are distinguished in the simulation view, though both are the same particle (photons with different energies). For example, optical photon is used for Cerenkov light and scintillation light.
   f. geantino/charged geantino

      Geantino and charged geantino are virtual particles for simulation which do not interact with materials and undertake transportation processes only.

2. nuclei

   Any kinds of nucleus can be used in Geant4, such as alpha(He-4), uranium-238 and excited states of carbon-14. In addition, Geant4 provides hyper-nuclei. Nuclei in Geant4 are divided into two groups from the viewpoint of implementation.
   a. light nuclei

      Light nuclei frequently used in simulation, e.g., alpha, deuteron, He3, triton.
   b. heavy nuclei (including hyper-nuclei)

      Nuclei other than those defined in the previous category.

   Note that G4ParticleDefinition represents nucleus state and G4DynamicParticle represents atomic state with some nucleus. Both alpha particle with charge of +2e and helium atom with no charge aggregates the same "particle definition" of G4Alpha, but different G4DynamicParticle objects should be assigned to them. (Details can be found below)
3. short-lived particles

   Particles with very short life time decay immediately and are never tracked in the detector geometry. These particles are usually used only inside physics processes to implement some models of interactions. *G4VShortLivedParticle* is provided as the base class for these particles. All classes related to particles in this category can be found in `shortlived` sub-directory under the `particles` directory.
   a. quarks/di-quarks

      For example, all 6 quarks.
   b. gluon
   c. baryon excited states with very short life

      For example, spin 3/2 baryons and anti-baryons
   d. meson excited states with very short life

      For example, spin 1 vector bosons

5.3.2.3. Implementation of particles

Single object created in the initialization : Categories a, b-1

These particles are frequently used for tracking in Geant4. An individual class is defined for each particle in these categories. The object in each class is unique. The user can get pointers to these objects by using static methods in their own classes. The unique object for each class is created when its static method is called in the ``initialization phase".

On-the-fly creation: Category b-2

Ions will travel in a detector geometry and should be tracked, however, the number of ions which may be used for hadronic processes is so huge that ions are dynamically created by requests from processes (and users). Each ion corresponds to one object of the *G4Ions* class. *G4IonTable* class is a dictionary for ions. `G4ParticleTable::GetIon()` method invokes `G4IonTable::GetIon()` method to create ions on the fly.

Users can register a *G4IsotopeTable* to the *G4IonTable*. *G4IsotopeTable* describes properties of ions (exited energy, decay modes, life time and magnetic moments), which are used to create ions.

Processes attached to heavy ions are same as those for *G4GenericIon* class. In other words, you need to create *G4GenericIon* and attach processes to it if you want to use heavy ions.

G4ParticleGun can shoot any heavy ions with /gun/ions command after ``ion" is selected by /gun/particle command.

Dynamic creation by processes: Category c

Particle types in this category are are not created by default, but will only be created by request from processes or directly by users. Each shortlived particle corresponds to one object of a class derived from *G4VshortLivedParticle*, and it will be created dynamically during the ``initialization phase".

5.3.2.4. G4ParticleDefinition

The *G4ParticleDefinition* class has ``read-only" properties to characterize individual particles, such as name, mass, charge, spin, and so on. These properties are set during initialization of each particle. Methods to get these properties are listed in Table 5.2.

`G4String GetParticleName()`	particle name
`G4double GetPDGMass()`	mass
`G4double GetPDGWidth()`	decay width
`G4double GetPDGCharge()`	electric charge
`G4double GetPDGSpin()`	spin
`G4double GetPDGMagneticMoment()`	magnetic moment (0: not defined or no magnetic moment)
`G4int GetPDGiParity()`	parity (0:not defined)
`G4int GetPDGiConjugation()`	charge conjugation (0:not defined)
`G4double GetPDGIsospin()`	iso-spin
`G4double GetPDGIsospin3()`	3rd-component of iso-spin
`G4int GetPDGiGParity()`	G-parity (0:not defined)
`G4String GetParticleType()`	particle type
`G4String GetParticleSubType()`	particle sub-type
`G4int GetLeptonNumber()`	lepton number
`G4int GetBaryonNumber()`	baryon number
`G4int GetPDGEncoding()`	particle encoding number by PDG
`G4int GetAntiPDGEncoding()`	encoding for anti-particle of this particle

Table 5.2. Methods to get particle properties.

Table 5.3 shows the methods of *G4ParticleDefinition* for getting information about decay modes and the life time of the particle.

`G4bool GetPDGStable()`	stable flag
`G4double GetPDGLifeTime()`	life time
`G4DecayTable* GetDecayTable()`	decay table

Table 5.3. Methods to get particle decay modes and life time.

Users can modify these properties, though the other properties listed above can not be change without rebuilding the libraries.

Each particle has its own *G4ProcessManger* object that manages a list of processes applicable to the particle.(see Section 2.5.2)

5.3.3. Dynamic particle

The *G4DynamicParticle* class has kinematics information for the particle and is used for describing the dynamics of physics processes. The properties in *G4DynamicParticle* are listed in Table 5.4.

`G4double theDynamicalMass`	dynamical mass
`G4ThreeVector theMomentumDirection`	normalized momentum vector
`G4ParticleDefinition* theParticleDefinition`	definition of particle
`G4double theDynamicalSpin`	dynamical spin (i.e. total angular momentum as a ion/atom)
`G4ThreeVector thePolarization`	polarization vector
`G4double theMagneticMoment`	dynamical magnetic moment (i.e. total magnetic moment as a ion/atom)
`G4double theKineticEnergy`	kinetic energy
`G4double theProperTime`	proper time
`G4double theDynamicalCharge`	dynamical electric charge (i.e. total electric charge as a ion/atom)
`G4ElectronOccupancy* theElectronOccupancy`	electron orbits for ions

Table 5.4. Methods to set/get cut off values.

Here, the dynamical mass is defined as the mass for the dynamic particle. For most cases, it is same as the mass defined in *G4ParticleDefinition* class (i.e. mass value given by `GetPDGMass()` method). However, there are two exceptions.

- resonance particle
- ions

Resonance particles have large mass width and the total energy of decay products at the center of mass system can be different event by event.

As for ions, *G4ParticleDefintion* defines a nucleus and *G4DynamicParticle* defines an atom. *G4ElectronOccupancy* describes state of orbital electrons. So, the dynamic mass can be different from the PDG mass by the mass of electrons (and their binding energy). In addition, the dynamical charge, spin and magnetic moment are those of the atom/ion (i.e. including nucleus and orbit electrons).

Decay products of heavy flavor particles are given in many event generators. In such cases, *G4VPrimaryGenerator* sets this information in `*thePreAssignedDecayProducts`. In addition, decay time of the particle can be set arbitrarily time by using `PreAssignedDecayProperTime`.

5.4. Production Threshold versus Tracking Cut

5.4.1. General considerations

We have to fulfill two contradictory requirements. It is the responsibility of each individual **process** to produce secondary particles according to its own capabilities. On the other hand, it is only the Geant4 kernel (i.e., tracking) which can ensure an overall coherence of the simulation.

The general principles in Geant4 are the following:

1. Each **process** has its intrinsic limit(s) to produce secondary particles.
2. All particles produced (and accepted) will be tracked up to **zero range**.
3. Each **particle** has a suggested cut in range (which is converted to energy for all materials), and defined via a `SetCut()` method (see Section 2.4.2).

Points 1 and 2 imply that the cut associated with the **particle** is a (recommended) **production** threshold of secondary particles.

5.4.2. Set production threshold (`SetCut` methods)

As already mentioned, each kind of particle has a suggested production threshold. Some of the processes will not use this threshold (e.g., decay), while other processes will use it as a default value for their intrinsic limits (e.g., ionisation and bremsstrahlung).

See Section 2.4.2 to see how to set the production threshold.

5.4.3. Apply cut

The `DoIt` methods of each process can produce secondary particles. Two cases can happen:

- a process sets its intrinsic limit greater than or equal to the recommended production threshold. OK. Nothing has to be done (nothing can be done !).
- a process sets its intrinsic limit smaller than the production threshold (for instance 0).

The list of secondaries is sent to the *SteppingManager* via a *ParticleChange* object.

Before being recopied to the temporary stack for later tracking, the particles below the production threshold will be kept or deleted according to the safe mechanism explained hereafter.

- The *ParticleDefinition* (or *ParticleWithCuts*) has a boolean data member: `ApplyCut`.
- `ApplyCut` is OFF: do nothing. All the secondaries are stacked (and then tracked later on), regardless of their initial energy. The Geant4 kernel respects the best that the physics can do, but neglects the overall coherence and the efficiency. Energy conservation is respected as far as the processes know how to handle correctly the particles they produced!
- `ApplyCut` in ON: the *TrackingManager* checks the range of each secondary against the production threshold and against the safety. The particle is stacked if `range > min(cut,safety).`
  - If not, check if the process has nevertheless set the flag ``good for tracking'' and then stack it (see Section 5.4.4 below for the explanation of the `GoodForTracking` flag).
  - If not, recuperate its kinetic energy in the `localEnergyDeposit`, and set `tkin=0`.
  - Then check in the *ProcessManager* if the vector of *ProcessAtRest* is not empty. If yes, stack the particle for performing the ``Action At Rest'' later. If not, and only in this case, abandon this secondary.

With this sophisticated mechanism we have the global cut that we wanted, but with energy conservation, and we respect boundary constraint (safety) and the wishes of the processes (via ``good for tracking'').

5.4.4. Why produce secondaries below threshold?

A process may have good reasons to produce particles below the recommended threshold:

- checking the range of the secondary versus geometrical quantities like safety may allow one to realize the possibility that the produced particle, even below threshold, will reach a sensitive part of the detector;
- another example is the gamma conversion: the positron is always produced, even at zero energy, for further annihilation.

These secondary particles are sent to the ``Stepping Manager'' with a flag `GoodForTracking` to pass the filter explained in the previous section (even when `ApplyCut` is ON).

5.4.5. Cuts in stopping range or in energy?

The cuts in stopping range allow one to say that the energy has been released at the correct space position, limiting the approximation within a given distance. On the contrary, cuts in energy imply accuracies of the energy depositions which depend on the material.

5.4.6. Summary

In summary, we do not have tracking cuts; we only have production thresholds in range. All particles produced and accepted are tracked up to zero range.

It must be clear that the overall coherency that we provide cannot go beyond the capability of processes to produce particles down to the recommended threshold.

In other words a process can produce the secondaries down to the recommended threshold, and by interrogating the geometry, or by realizing when mass-to-energy conversion can occur, recognize when particles below the threshold have to be produced.

5.4.7. Special tracking cuts

One may need to cut given particle types in given volumes for optimisation reasons. This decision is under user control, and can happen for particles during tracking as well.

The user must be able to apply these special cuts only for the desired particles and in the desired volumes, without introducing an overhead for all the rest.

The approach is as follows:

- special user cuts are registered in the *UserLimits* class (or its descendant), which is associated with the logical volume class.

  The current default list is:
  - max allowed step size
  - max total track length
  - max total time of flight
  - min kinetic energy
  - min remaining range

  The user can instantiate a *UserLimits* object only for the desired logical volumes and do the association.

  The first item (max step size) is automatically taken into account by the G4 kernel while the others items must be managed by the user, as explained below.

  Example(see novice/N02): in the Tracker region, in order to force the step size not to exceed 1/10 of the Tracker thickness, it is enough to put the following code in `DetectorConstruction::Construct()`:

```
G4double maxStep = 0.1*TrackerLength;
logicTracker->SetUserLimits(new G4UserLimits(maxStep));
```

  and in `PhysicsList`, the process `G4StepLimiter` needs to be attached to each particle's process manager where step limitation in the Tracker region is required:

```
// Step limitation seen as a process
G4StepLimiter* stepLimiter = new G4StepLimiter();
pmanager->AddDiscreteProcess(StepLimiter);
```

  The *G4UserLimits* class is in `source/global/management`.
- Concerning the others cuts, the user must define dedicaced process(es). He registers this process (or its descendant) only for the desired particles in their process manager. He can apply his cuts in the `DoIt` of this process, since, via *G4Track*, he can access the logical volume and *UserLimits*.

  An example of such process (called *UserSpecialCuts*) is provided in the repository, but not inserted in any process manager of any particle.

  Example: neutrons. One may need to abandon the tracking of neutrons after a given time of flight (or a charged particle in a magnetic field after a given total track length ... etc ...).

  Example(see novice/N02): in the Tracker region, in order to force the total time of flight of the neutrons not to exceed 10 milliseconds, put the following code in `DetectorConstruction::Construct()`:

```
G4double maxTime = 10*ms;
logicTracker->SetUserLimits(new G4UserLimits(DBL_MAX,DBL_MAX,maxTime));
```

and put the following code in `N02PhysicsList`:

```
G4ProcessManager* pmanager = G4Neutron::Neutron->GetProcessManager();
pmanager->AddProcess(new G4UserSpecialCuts(),-1,-1,1);
```

(The default *G4UserSpecialCuts* class is in `source/processes/transportation`.)

5.5. Cuts per Region

5.5.1. General Concepts

Beginning with Geant4 version 5.1, the concept of a region has been defined for use in geometrical descriptions. Details about regions and how to use them are available in Section 4.1.3.1. As an example, suppose a user defines three regions, corresponding to the tracking volume, the calorimeter and the bulk structure of a detector. For performance reasons, the user may not be interested in the detailed development of electromagnetic showers in the insensitive bulk structure, but wishes to maintain the best possible accuracy in the tracking region. In such a use case, Geant4 allows the user to set different production thresholds ("cuts") for each geometrical region. This ability, referred to as "cuts per region", is also a new feature provided by the Geant4 5.1 release. The general concepts of production thresholds were presented in the Section 5.4.

Please note that this new feature is intended only for users who

1. are simulating the most complex geometries, such as an LHC detector, and
2. are experienced in simulating electromagnetic showers in matter.

We strongly recommend that results generated with this new feature be compared with results using the same geometry and uniform production thresholds. Setting completely different cut values for individual regions may break the coherent and comprehensive accuracy of the simulation. Therefore cut values should be carefully optimized, based on a comparison with results obtained using uniform cuts.

5.5.2. Default Region

The world volume is treated as a region by default. A *G4Region* object is automatically assigned to the world volume and is referred to as the "default region". The production cuts for this region are the defaults which are defined in the *UserPhysicsList*. Unless the user defines different cut values for other regions, the cuts in the default region will be used for the entire geometry.

Please note that the default region and its default production cuts are created and set automatically by *G4RunManager*. The user is **not** allowed to set a region to the world volume, **nor** to assign other production cuts to the default region.

5.5.3. Assigning Production Cuts to a Region

In the `SetCuts()` method of the user's physics list, the user must first define the default cuts. Then a *G4ProductionCuts* object must be created and initialized with the cut value desired for a given region. This object must in turn be assigned to the region object, which can be accessed by name from the *G4RegionStore*. An example `SetCuts()` code follows.

Example 5.10. Setting production cuts to a region

```
void MyPhysicsList::SetCuts()
{
  // default production thresholds for the world volume
  SetCutsWithDefault();

  // Production thresholds for detector regions
  G4Region* region;
  G4String regName;
  G4ProductionCuts* cuts;

  regName = "tracker";
  region = G4RegionStore::GetInstance()->GetRegion(regName);
  cuts = new G4ProductionCuts;
  cuts->SetProductionCut(0.01*mm); // same cuts for gamma, e- and e+
  region->SetProductionCuts(cuts);

  regName = "calorimeter";
  region = G4RegionStore::GetInstance()->GetRegion(regName);
  cuts = new G4ProductionCuts;
  cuts->SetProductionCut(0.01*mm,G4ProductionCuts::GetIndex("gamma"));
  cuts->SetProductionCut(0.1*mm,G4ProductionCuts::GetIndex("e-"));
  cuts->SetProductionCut(0.1*mm,G4ProductionCuts::GetIndex("e+"));
  region->SetProductionCuts(cuts);
}
```

5.6. Physics Table

5.6.1. General Concepts

In Geant4, physics processes use many tables of cross sections, energy losses and other physics values. Before the execution of an event loop, the `BuildPhysicsTable()` method of *G4VProcess* is invoked for all processes and as a part of initialisation procedure cross section tables are prepared. Energy loss processes calculate cross section and/or energy loss values for each material and for each production cut value assigned to each material. A change in production cut values therefore require these cross sections to be re-calculated. Cross sections for hadronic processes and gamma processes do not depend on the production cut.

The *G4PhysicsTable* class is used to handle cross section tables. *G4PhysicsTable* is a collection of instances of *G4PhysicsVector* (and derived classes), each of which has cross section values for a particle within a given energy range traveling in a material. By default the linear interpolation is used, alternatively spline may be used if the flag of spline is activated by *SetSpline* method of the *G4PhysicsVector*

5.6.2. Material-Cuts Couple

Users can assign different production cuts to different regions (see Section 5.5). This means that if the same material is used in regions with different cut values, the processes need to prepare several different cross sections for that material.

The *G4ProductionCutsTable* has *G4MaterialCutsCouple* objects, each of which consists of a material paired with a cut value. These *G4MaterialCutsCouple*s are numbered with an index which is the same as the index of a *G4PhysicsVector* for the corresponding *G4MaterialCutsCouple*in the *G4PhysicsTable*. The list of *MaterialCutsCouple*s used in the current geometry setup is updated before starting the event loop in each run.

5.6.3. File I/O for the Physics Table

Calculated physics tables for electromagnetic processes can be stored in files. The user may thus eliminate the time required for the calculation of physics tables by retrieving them from the files.

Using the built-in user command "**storePhysicsTable**" (see Section 7.1), stores physics tables in files. Information on materials and cuts defined in the current geometry setup are stored together with physics tables because calculated values in the physics tables depend on *MaterialCutsCouple*. Note that physics tables are calculated

before the event loop, not in the initialization phase. So, at least one event must be executed before using the "**storePhysicsTable**" command.

Calculated physics tables can be retrieved from files by using the "**retrievePhysicsTable**" command. Materials and cuts from files are compared with those defined in the current geometry setup, and only physics vectors corresponding to the *MaterialCutsCouple*s used in the current setup are restored. Note that nothing happens just after the "**retrievePhysicsTable**" command is issued. Restoration of physics tables will be executed in parallel with the calculation of physics tables.

5.6.4. Building the Physics Table

In the `G4RunManagerKernel::RunInitialization()` method, after the list of *MaterialCutsCouple*s is updated, the `G4VUserPhysicsList::BuildPhysicsTable()` method is invoked to build physics tables for all processes.

Initially, the `G4VProcess::PreparePhysicsTable()` method is invoked. Each process creates *G4PhysicsTable* objects as necessary. It then checks whether the *MaterialCutsCouple*s have been modified after a run to determine if the corresponding physics vectors can be used in the next run or need to be re-calculated.

Next, the `G4VProcess::RetrievePhysicsTable()` method is invoked if the `G4VUserPhysicsList::fRetrievePhysicsTable` flag is asserted. After checking materials and cuts in files, physics vectors corresponding to the *MaterialCutsCouple*s used in the current setup are restored.

Finally, the `G4VProcess::BuildPhysicsTable()` method is invoked and only physics vectors which need to be re-calculated are built.

5.7. User Limits

5.7.1. General Concepts

The user can define artificial limits affecting to the Geant4 tracking.

```
G4UserLimits(G4double uStepMax = DBL_MAX,
             G4double uTrakMax = DBL_MAX,
             G4double uTimeMax = DBL_MAX,
             G4double uEkinMin = 0.,
             G4double uRangMin = 0. );
```

`uStepMax`	Maximum step length
`uTrakMax`	Maximum total track length
`uTimeMax`	Maximum global time for a track
`uEkinMin`	Minimum remaining kinetic energy for a track
`uRangMin`	Minimum remaining range for a track

Note that `uStepMax` is affecting to each step, while all other limits are affecting to a track.

The user can set `G4UserLimits` to logical volume and/or to a region. User limits assigned to logical volume do not propagate to daughter volumes, while User limits assigned to region propagate to daughter volumes unless daughters belong to another region. If both logical volume and associated region have user limits, those of logical volume win.

5.7.2. Processes co-working with G4UserLimits

In addition to instantiating `G4UserLimits` and setting it to logical volume or region, the user has to assign the following process(es) to particle types he/she wants to affect. If none of these processes is assigned, that kind of particle is not affected by `G4UserLimits`.

Limitation to step (`uStepMax`)
: `G4StepLimiter` process must be defined to affected particle types. This process limits a step, but it does not kill a track.

Limitations to track (`uTrakMax, uTimeMax, uEkinMin, uRangMin`)
: `G4UserSpecialCuts` process must be defined to affected particle types. This process limits a step and kills the track when the track comes to one of these limits. Step limitation occurs only for the final step.

Example of `G4UserLimits` can be found in examples/novice/N02 : see `DetectorConstruction` and `PhysicsList`.

5.8. Track Error Propagation

The error propagation package serves to propagate one particle together with its error from a given trajectory state until a user-defined target is reached (a surface, a volume, a given track length,...).

5.8.1. Physics

The error propagator package computes the average trajectory that a particle would follow. This means that the physics list must have the following characteristics:

- No multiple scattering
- No random fluctuations for energy loss
- No creation of secondary tracks
- No hadronic processes

It has also to be taken into account that when the propagation is done backwards (in the direction opposed to the one the original track traveled) the energy loss has to be changed into an energy gain.

All this is done in the `G4ErrorPhysicsList` class, that is automatically set by `G4ErrorPropagatorManager` as the GEANT4 physics list. It sets `G4ErrorEnergyLoss` as unique electromagnetic process. This process uses the GEANT4 class `G4EnergyLossForExtrapolator` to compute the average energy loss for forwards or backwards propagation. To avoid getting too different energy loss calculation when the propagation is done forwards (when the energy at the beginning of the step is used) or backwards (when the energy at the end of the step is used, always smaller than at the beginning) `G4ErrorEnergyLoss` computes once the energy loss and then replaces the original energy loss by subtracting/adding half of this value (what is approximately the same as computing the energy loss with the energy at the middle of the step). In this way, a better calculation of the energy loss is obtained with a minimal impact on the total CPU time.

The user may use his/her own physics list instead of `G4ErrorPhysicsList`. As it is not needed to define a physics list when running this package, the user may have not realized that somewhere else in his/her application it has been defined; therefore a warning will be sent to advert the user that he is using a physics list different to `G4ErrorPhysicsList`. If a new physics list is used, it should also initialize the `G4ErrorMessenger` with the classes that serve to limit the step:

```
G4ErrorEnergyLoss* eLossProcess = new G4ErrorEnergyLoss;
G4ErrorStepLengthLimitProcess* stepLengthLimitProcess = new G4ErrorStepLengthLimitProcess;
G4ErrorMagFieldLimitProcess* magFieldLimitProcess = new G4ErrorMagFieldLimitProcess;
new G4ErrorMessenger( stepLengthLimitProcess, magFieldLimitProcess, eLossProcess );
```

To ease the use of this package in the reconstruction code, the physics list, whether `G4ErrorPhysicsList` or the user's one, will be automatically initialized before starting the track propagation if it has not been done by the user.

5.8.2. Trajectory state

The user has to provide the particle trajectory state at the initial point. To do this it has to create an object of one of the children classes of `G4ErrorTrajState`, providing:

- Particle type
- Position
- Momentum
- Trajectory error matrix

```
G4ErrorTrajState( const G4String& partType,
                  const G4Point3D& pos,
                  const G4Vector3D& mom,
                  const G4ErrorTrajErr& errmat = G4ErrorTrajErr(5,0) );
```

A particle trajectory is characterized by five independent variables as a function of one parameter (e.g. the path length). Among the five variables, one is related to the curvature (to the absolute value of the momentum), two are related to the direction of the particle and the other two are related to the spatial location.

There are two possible representations of these five parameters in the error propagator package: as a free trajectory state, class `G4ErrorTrajStateFree`, or as a trajectory state on a surface, class `G4ErrorTrajStateonSurface`.

5.8.2.1. Free trajectory state

In the free trajectory state representation the five trajectory parameters are

- G4double fInvP
- G4double fLambda
- G4double fPhi
- G4double fYPerp
- G4double fZPerp

where `fInvP` is the inverse of the momentum. `fLambda` and `fPhi` are the dip and azimuthal angles related to the momentum components in the following way:
`p_x = p cos(lambda) cos(phi) p_y = p cos(lambda) sin(phi) p_z = p sin(lambda)`

that is, `lambda = 90 - theta`, where `theta` is the usual angle with respect to the Z axis.

`fYperp` and `fZperp` are the coordinates of the trajectory in a local orthonormal reference frame with the X axis along the particle direction, the Y axis being parallel to the X-Y plane (obtained by the vectorial product of the global Z axis and the momentum).

5.8.2.2. Trajectory state on a surface

In the trajectory state on a surface representation the five trajectory parameters are

- G4double fInvP
- G4double fPV
- G4double fPW
- G4double fV
- G4double fW

where `fInvP` is the inverse of the momentum; `fPV` and `fPW` are the momentum components in an orthonormal coordinate system with axis U, V and W; `fV` and `fW` are the position components on this coordinate system.
For this representation the user has to provide the plane where the parameters are calculated. This can be done by providing two vectors, V and W, contained in the plane:

```
G4ErrorSurfaceTrajState( const G4String& partType,
                         const G4Point3D& pos,
                         const G4Vector3D& mom,
                         const G4Vector3D& vecV,
                         const G4Vector3D& vecW,
                         const G4ErrorTrajErr& errmat = G4ErrorTrajErr(5,0) );
```

or by providing a plane

```
G4ErrorSurfaceTrajState( const G4String& partType,
                         const G4Point3D& pos,
                         const G4Vector3D& mom,
                         const G4Plane3D& plane,
                         const G4ErrorTrajErr& errmat = G4ErrorTrajErr(5,0) );
```

In this second case the vector V is calculated as the vector in the plane perpendicular to the global vector X (if the plane normal is equal to X, Z is used instead) and W is calculated as the vector in the plane perpendicular to V.

5.8.3. Trajectory state error

The 5X5 error matrix should also be provided at the creation of the trajectory state as a `G4ErrorTrajErr` object. If it is not provided a default object will be created filled with null values.

Currently the `G4ErrorTrajErr` is a `G4ErrorSymMatrix`, a simplified version of `CLHEP HepSymMatrix`.

The error matrix is given in units of GeV and cm. Therefore you should do the conversion if your code is using other units.

5.8.4. Targets

The user has to define up to where the propagation must be done: the target. The target can be a surface `G4ErrorSurfaceTarget`, which is not part of the GEANT4 geometry. It can also be the surface of a GEANT4 volume `G4ErrorGeomVolumeTarget`, so that the particle will be stopped when it enters this volume. Or it can be that the particle is stopped when a certain track length is reached, by implementing a `G4ErrorTrackLengthTarget`.

5.8.4.1. Surface target

When the user chooses a `G4ErrorSurfaceTarget` as target, the track is propagated until the surface is reached. This surface is not part of GEANT4 geometry, but usually traverses many GEANT4 volumes. The class `G4ErrorNavigator` takes care of the double navigation: for each step the step length is calculated as the minimum of the step length in the full geometry (up to a GEANT4 volume surface) and the distance to the user-defined surface. To do it, `G4ErrorNavigator` inherits from `G4Navigator` and overwrites the methods `ComputeStep()` and `ComputeSafety()`. Two types of surface are currently supported (more types could be easily implemented at user request): plane and cylindrical.

5.8.4.1.1. Plane surface target

`G4ErrorPlaneSurfaceTarget` implements an infinite plane surface. The surface can be given as the four coefficients of the plane equation `ax+by+cz+d = 0`:

```
  G4ErrorPlaneSurfaceTarget(G4double a=0,
                            G4double b=0,
                            G4double c=0,
                            G4double d=0);
```

or as the normal to the plane and a point contained in it:

```
  G4ErrorPlaneSurfaceTarget(const G4Normal3D &n,
                            const G4Point3D &p);
```

or as three points contained in it:

```
G4ErrorPlaneSurfaceTarget(const G4Point3D &p1,
                          const G4Point3D &p2,
                          const G4Point3D &p3);
```

5.8.4.1.2. Cylindrical surface target

`G4ErrorCylSurfaceTarget` implements an infinite-length cylindrical surface (a cylinder without end-caps). The surface can be given as the radius, the translation and the rotation

```
G4ErrorCylSurfaceTarget( const G4double& radius,
                         const G4ThreeVector& trans=G4ThreeVector(),
                         const G4RotationMatrix& rotm=G4RotationMatrix() );
```

or as the radius and the affine transformation

```
G4ErrorCylSurfaceTarget( const G4double& radius,
                         const G4AffineTransform& trans );
```

5.8.4.2. Geometry volume target

When the user chooses a `G4ErrorGeomVolumeTarget` as target, the track is propagated until the surface of a GEANT4 volume is reached. User can choose if the track will be stopped only when the track enters the volume, only when the track exits the volume or in both cases.
The object has to be instantiated giving the name of a logical volume existing in the geometry:

```
G4ErrorGeomVolumeTarget( const G4String& name );
```

5.8.4.3. Track Length target

When the user chooses a `G4ErrorTrackLengthTarget` as target, the track is propagated until the given track length is reached.
The object has to be instantiated giving the value of the track length:

```
G4ErrorTrackLengthTarget(const G4double maxTrkLength );
```

It is implemented as a `G4VDiscreteProcess` and it limits the step in `PostStepGetPhysicalInteractionLength`. To ease its use, the process is registered to all particles in the constructor.

5.8.5. Managing the track propagation

The user needs to propagate just one track, so there is no need of run and events. neither of `G4VPrimaryGeneratorAction`. `G4ErrorPropagator` creates a track from the information given in the `G4ErrorTrajState` and manages the step propagation. The propagation is done by the standard GEANT4 methods, invoking `G4SteppingManager::Stepping()` to propagate each step.

After one step is propagated, `G4ErrorPropagator` takes cares of propagating the track errors for this step, what is done by `G4ErrorTrajStateFree::PropagateError()`. The equations of error propagation are only implemented in the representation of `G4ErrorTrajStateFree`. Therefore if the user has provided instead a `G4ErrorTrajStateOnSurface` object, it will be transformed into a `G4ErrorTrajStateFree` at the beginning of tracking, and at the end it is converted back into `G4ErrorTrajStateOnSurface` on the target surface (on the normal plane to the surface at the final point).

The user `G4VUserTrackingAction::PreUserTrackingAction( const G4Track* )` and `G4VUserTrackingAction::PreUserTrackingAction( const G4Track* )` are also invoked at the beginning and at the end of the track propagation.

`G4ErrorPropagator` stops the tracking when one of the three conditions is true:

- Energy is exhausted
- World boundary is reached
- User-defined target is reached

In case the defined target is not reached, `G4ErrorPropagator::Propagate()` returns a negative value.

The propagation of a trajectory state until a user defined target can be done by invoking the method of `G4ErrorPropagatorManager`

```
G4int Propagate( G4ErrorTrajState* currentTS, const G4ErrorTarget* target,
                 G4ErrorMode mode = G4ErrorMode_PropForwards );
```

You can get the pointer to the only instance of `G4ErrorPropagatorManager` with

```
G4ErrorPropagatorManager* g4emgr = G4ErrorPropagatorManager::GetErrorPropagatorManager();
```

Another possibility is to invoke the propagation step by step, returning control to the user after each step. This can be done with the method

```
G4int PropagateOneStep( G4ErrorTrajState* currentTS,
                        G4ErrorMode mode = G4ErrorMode_PropForwards );
```

In this case you should register the target first with the command

```
G4ErrorPropagatorData::GetG4ErrorPropagatorData()->SetTarget( theG4eTarget );
```

5.8.5.1. Error propagation

As in the GEANT3-based GEANE package, the error propagation is based on the equations of the European Muon Collaboration, that take into account:

- Error from curved trajectory in magnetic field
- Error from multiple scattering
- Error from ionization

The formulas assume propagation along an helix. This means that it is necessary to make steps small enough to assure magnetic field constantness and not too big energy loss.

5.8.6. Limiting the step

There are three ways to limit the step. The first one is by using a fixed length value. This can be set by invoking the user command :

```
G4UImanager::GetUIpointer()->ApplyCommand("/geant4e/limits/stepLength MY_VALUE MY_UNIT");
```

The second one is by setting the maximum percentage of energy loss in the step (or energy gain is propagation is backwards). This can be set by invoking the user command :

```
G4UImanager::GetUIpointer()->ApplyCommand("/geant4e/limits/energyLoss MY_VALUE");
```

The last one is by setting the maximum difference between the value of the magnetic field at the beginning and at the end of the step. Indeed what is limited is the curvature, or exactly the value of the magnetic field divided by the value of the momentum transversal to the field. This can be set by invoking the user command :

```
G4UImanager::GetUIpointer()->ApplyCommand("/geant4e/limits/magField MY_VALUE");
```

The classes that limit the step are implemented as GEANT4 processes. Therefore, the invocation of the above-mentioned commands should only be done after the initialization (for example after `G4ErrorPropagatorManager::InitGeant4e()`.

Chapter 6. User Actions

6.1. Mandatory User Actions and Initializations

Geant4 has three virtual classes whose methods the user must override in order to implement a simulation. They require the user to define the detector, specify the physics to be used, and describe how initial particles are to be generated.

`G4VUserDetectorConstruction`

Example 6.1. `G4VUserDetectorConstruction`

```
class G4VUserDetectorConstruction
{
  public:
    G4VUserDetectorConstruction();
    virtual ~G4VUserDetectorConstruction();

  public:
    virtual G4VPhysicalVolume* Construct() = 0;
};
```

`G4VUserPhysicsList`

This is an abstract class for constructing particles and processes. The user must derive a concrete class from it and implement three virtual methods:

- `ConstructParticle()` to instantiate each requested particle type,
- `ConstructPhysics()` to instantiate the desired physics processes and register each of them with the process managers of the appropriate particles, and
- `SetCuts(G4double aValue)` to set a cut value in range for all particles in the particle table, which invokes the rebuilding of the physics table.

When called, the `Construct()` method of *G4VUserPhysicsList* first invokes `ConstructParticle()` and then `ConstructProcess()`. The `ConstructProcess()` method must always invoke the `AddTransportation()` method in order to insure particle transportation. `AddTransportation()` must never be overridden.

G4VUserPhysicsList provides several utility methods for the implementation of the above virtual methods. They are presented with comments in the class declaration in Example 6.2.

Example 6.2. `G4VUserPhysicsList`

```
class G4VUserPhysicsList
{
  public:
    G4VUserPhysicsList();
    virtual ~G4VUserPhysicsList();

  public:  // with description
    // By calling the "Construct" method,
    // particles and processes are created
    void Construct();

  protected: // with description
   // These two methods of  ConstructParticle() and ConstructProcess()
   // will be invoked in the Construct() method.

   // each particle type will be instantiated
   virtual void ConstructParticle() = 0;

   // each physics process will be instantiated and
   // registered to the process manager of each particle type
   virtual void ConstructProcess() = 0;

  protected: // with description
   //  User must invoke this method in his ConstructProcess()
   //  implementation in order to insures particle transportation.
   //  !! Caution: this class must not be overriden !!
   void AddTransportation();

  ////////////////////////////////////////////////////////////
  public: // with description
   //  "SetCuts" method sets a cut value for all particle types
   //   in the particle table
   virtual void SetCuts() = 0;

  public:  // with description
   //  set/get the default cut value
   //  Calling SetDefaultCutValue causes re-calcuration of cut values
   //  and physics tables just before the next event loop
   void     SetDefaultCutValue(G4double newCutValue);
   G4double GetDefaultCutValue() const;
```

```
  ////////////////////////////////////////////////////////////////
  public: // with description
    // Invoke BuildPhysicsTable for all processes for all particles
    // In case of "Retrieve" flag is ON, PhysicsTable will be
    // retrieved from files
    void BuildPhysicsTable();

   // do BuildPhysicsTable for specified particle type
    void BuildPhysicsTable(G4ParticleDefinition* );

     // Store PhysicsTable together with both material and cut value
    // information in files under the specified directory.
    //  (return true if files are sucessfully created)
    G4bool  StorePhysicsTable(const G4String& directory = ".");

    // Return true if "Retrieve" flag is ON.
    // (i.e. PhysicsTable will be retrieved from files)
    G4bool  IsPhysicsTableRetrieved() const;
    G4bool  IsStoredInAscii() const;

    // Get directory path for physics table files.
    const G4String& GetPhysicsTableDirectory() const;

    // Set "Retrieve" flag
    // Directory path can be set together.
    // Null string (default) means directory is not changed
    // from the current value
    void    SetPhysicsTableRetrieved(const G4String& directory = "");
    void    SetStoredInAscii();

    // Reset "Retrieve" flag
    void    ResetPhysicsTableRetrieved();
```

```
    void    ResetStoredInAscii();

 ////////////////////////////////////////////////////////////////////
  public: // with description
    // Print out the List of registered particles types
    void DumpList() const;

  public: // with description
    // Request to print out information of cut values
    // Printing will be performed when all tables are made
    void DumpCutValuesTable(G4int nParticles=3);

    // The following method actually trigger the print-out requested
    // by the above method. This method must be invoked by RunManager
    // at the proper moment.
    void DumpCutValuesTableIfRequested();

  public: // with description
    void  SetVerboseLevel(G4int value);
    G4int GetVerboseLevel() const;
    // set/get controle flag for output message
    //  0: Silent
    //  1: Warning message
    //  2: More
```

```
  ////////////////////////////////////////////////////////////////////////
  public: // with description
   //  "SetCutsWithDefault" method sets the default cut value
   //   for all particles for the default region.
   void SetCutsWithDefault();

   // Following are utility methods for SetCuts

   // SetCutValue sets a cut value for a particle type for the default region
   void SetCutValue(G4double aCut, const G4String& pname);

   // SetCutValue sets a cut value for a particle type for a region
   void SetCutValue(G4double aCut, const G4String& pname, const G4String& rname);

   // Invoke SetCuts for specified particle for a region
   // If the pointer to the region is NULL, the default region is used
   // In case of "Retrieve" flag is ON,
   // Cut values will be retrieved from files
   void SetParticleCuts(G4double cut,G4ParticleDefinition* particle,G4Region* region=0);

   // Invoke SetCuts for all particles in a region
   void SetCutsForRegion(G4double aCut, const G4String& rname);

   // Following are utility methods are obsolete
   void ResetCuts();

//////////////////////////////////////////////////////////////////////
  public:
   // Get/SetApplyCuts gets/sets the flag for ApplyCuts
   void SetApplyCuts(G4bool value, const G4String& name);
   G4bool GetApplyCuts(const G4String& name) const;

//////////////////////////////////////////////////////////////////////////////
  protected:
    // do BuildPhysicsTable for make the integral schema
    void BuildIntegralPhysicsTable(G4VProcess* ,G4ParticleDefinition*  );


  protected:
    // Retrieve PhysicsTable from files for proccess belongng the particle.
    // Normal BuildPhysics procedure of processes will be invoked,
    // if it fails (in case of Process's RetrievePhysicsTable returns false)
    virtual void  RetrievePhysicsTable(G4ParticleDefinition* ,
                                       const G4String& directory,
                                       G4bool          ascii = false);

   ////////////////////////////////////////////////////////////////
  protected:
    // adds new ProcessManager to all particles in the Particle Table
    //   this routine is used in Construct()
    void InitializeProcessManager();
```

```
  public: // with description
    // remove and delete ProcessManagers for all particles in tha Particle Table
    //    this routine is invoked from RunManager
    void RemoveProcessManager();

  public: // with description
    // add process manager for particles created on-the-fly
    void AddProcessManager(G4ParticleDefinition* newParticle,
                           G4ProcessManager*    newManager = 0 );

};
```

G4VUserPrimaryGeneratorAction

Example 6.3. G4VUserPrimaryGeneratorAction

```
    class G4VUserPrimaryGeneratorAction
    {
      public:
        G4VUserPrimaryGeneratorAction();
        virtual ~G4VUserPrimaryGeneratorAction();

      public:
        virtual void GeneratePrimaries(G4Event* anEvent) = 0;
    };
```

6.2. Optional User Actions

There are five virtual classes whose methods the user may override in order to gain control of the simulation at various stages. Each method of each action class has an empty default implementation, allowing the user to inherit and implement desired classes and methods. Objects of user action classes must be registered with `G4RunManager`.

6.2.1. Usage of User Actions

G4UserRunAction

This class has three virtual methods which are invoked by `G4RunManager` for each run:

`GenerateRun()`
: This method is invoked at the beginning of `BeamOn`. Because the user can inherit the class `G4Run` and create his/her own concrete class to store some information about the run, the `GenerateRun()` method is the place to instantiate such an object. It is also the ideal place to set variables which affect the physics table (such as production thresholds) for a particular run, because `GenerateRun()` is invoked before the calculation of the physics table.

`BeginOfRunAction()`
: This method is invoked before entering the event loop. A typical use of this method would be to initialize and/or book histograms for a particular run. This method is invoked after the calculation of the physics tables.

`EndOfRunAction()`
: This method is invoked at the very end of the run processing. It is typically used for a simple analysis of the processed run.

Example 6.4. G4UserRunAction

```
    class G4UserRunAction
    {
      public:
        G4UserRunAction();
        virtual ~G4UserRunAction();

      public:
        virtual G4Run* GenerateRun();
        virtual void BeginOfRunAction(const G4Run*);
        virtual void EndOfRunAction(const G4Run*);
    };
```

G4UserEventAction

This class has two virtual methods which are invoked by G4EventManager for each event:

beginOfEventAction()
: This method is invoked before converting the primary particles to G4Track objects. A typical use of this method would be to initialize and/or book histograms for a particular event.

endOfEventAction()
: This method is invoked at the very end of event processing. It is typically used for a simple analysis of the processed event. If the user wants to keep the currently processing event until the end of the current run, the user can invoke `fpEventManager->KeepTheCurrentEvent();` so that it is kept in *G4Run* object. This should be quite useful if you simulate quite many events and want to visualize only the most interest ones after the long execution. Given the memory size of an event and its contents may be large, it is the user's responsibility not to keep unnecessary events.

Example 6.5. G4UserEventAction

```
class G4UserEventAction
{
  public:
      G4UserEventAction() {;}
      virtual ~G4UserEventAction() {;}
      virtual void BeginOfEventAction(const G4Event*);
      virtual void EndOfEventAction(const G4Event*);
  protected:
      G4EventManager* fpEventManager;
};
```

G4UserStackingAction

This class has three virtual methods, ClassifyNewTrack, NewStage and PrepareNewEvent which the user may override in order to control the various track stacking mechanisms. ExampleN04 could be a good example to understand the usage of this class.

ClassifyNewTrack() is invoked by G4StackManager whenever a new G4Track object is "pushed" onto a stack by G4EventManager. ClassifyNewTrack() returns an enumerator, G4ClassificationOfNewTrack, whose value indicates to which stack, if any, the track will be sent. This value should be determined by the user. G4ClassificationOfNewTrack has four possible values:

- fUrgent - track is placed in the *urgent* stack
- fWaiting - track is placed in the *waiting* stack, and will not be simulated until the *urgent* stack is empty
- fPostpone - track is postponed to the next event
- fKill - the track is deleted immediately and not stored in any stack.

These assignments may be made based on the origin of the track which is obtained as follows:

```
G4int parent_ID = aTrack->get_parentID();
```

where

- parent_ID = 0 indicates a primary particle
- parent_ID > 0 indicates a secondary particle
- parent_ID < 0 indicates postponed particle from previous event.

NewStage() is invoked when the *urgent* stack is empty and the *waiting* stack contains at least one G4Track object. Here the user may kill or re-assign to different stacks all the tracks in the *waiting* stack by calling the

`stackManager->ReClassify()` method which, in turn, calls the `ClassifyNewTrack()` method. If no user action is taken, all tracks in the *waiting* stack are transferred to the *urgent* stack. The user may also decide to abort the current event even though some tracks may remain in the *waiting* stack by calling `stackManager->clear()`. This method is valid and safe only if it is called from the `G4UserStackingAction` class. A global method of event abortion is

```
G4UImanager * UImanager = G4UImanager::GetUIpointer();
UImanager->ApplyCommand("/event/abort");
```

`PrepareNewEvent()` is invoked at the beginning of each event. At this point no primary particles have been converted to tracks, so the *urgent* and *waiting* stacks are empty. However, there may be tracks in the *postponed-to-next-event* stack; for each of these the `ClassifyNewTrack()` method is called and the track is assigned to the appropriate stack.

Example 6.6. `G4UserStackingAction`

```
#include "G4ClassificationOfNewTrack.hh"

class G4UserStackingAction
{
  public:
      G4UserStackingAction();
      virtual ~G4UserStackingAction();
  protected:
      G4StackManager * stackManager;

  public:
//------------------------------------------------------------
// virtual methods to be implemented by user
//------------------------------------------------------------
//
      virtual G4ClassificationOfNewTrack
        ClassifyNewTrack(const G4Track*);
//
//------------------------------------------------------------
//
      virtual void NewStage();
//
//------------------------------------------------------------
//
      virtual void PrepareNewEvent();
//
//------------------------------------------------------------

};
```

G4UserTrackingAction

Example 6.7. G4UserTrackingAction

```
//---------------------------------------------------------------
//
// G4UserTrackingAction.hh
//
// Description:
//   This class represents actions taken place by the user at each
//   end of stepping.
//
//---------------------------------------------------------------

///////////////////////////
class G4UserTrackingAction
///////////////////////////
{

//--------
   public:
//--------

// Constructor & Destructor
   G4UserTrackingAction(){};
   virtual ~G4UserTrackingAction(){}

// Member functions
   virtual void PreUserTrackingAction(const G4Track*){}
   virtual void PostUserTrackingAction(const G4Track*){}

//-----------
   protected:
//-----------

// Member data
   G4TrackingManager* fpTrackingManager;

};
```

G4UserSteppingAction

Example 6.8. G4UserSteppingAction

```
//---------------------------------------------------------------
//
//  G4UserSteppingAction.hh
//
//  Description:
//    This class represents actions taken place by the user at each
//    end of stepping.
//
//---------------------------------------------------------------

////////////////////////////
class G4UserSteppingAction
////////////////////////////
{

//--------
   public:
//--------

// Constructor and destructor
   G4UserSteppingAction(){}
   virtual ~G4UserSteppingAction(){}

// Member functions
   virtual void UserSteppingAction(const G4Step*){}

//-----------
   protected:
//-----------

// Member data
   G4SteppingManager* fpSteppingManager;

};
```

6.2.2. Killing Tracks in User Actions and Energy Conservation

In either of user action classes described in the previous section, the user can implement an unnatural/unphysical action. A typical example is to kill a track, which is under the simulation, in the user stepping action. In this case the user have to be cautious of the total energy conservation. The user stepping action itself does not take care the energy or any physics quantity associated with the killed track. Therefore if the user want to keep the total energy of an event in this case, the lost track energy need to be recorded by the user.

The same is true for user stacking or tracking actions. If the user has killed a track in these actions the all physics information associated with it would be lost and, for example, the total energy conservation be broken.

If the user wants the Geant4 kernel to take care the total energy conservation automatically when he/she has killed artificially a track, the user has to use a killer process. For example if the user uses G4UserLimits and G4UserSpecialCuts process, energy of the killed track is added to the total energy deposit.

6.3. User Information Classes

Additional user information can be associated with various Geant4 classes. There are basically two ways for the user to do this:

- derive concrete classes from base classes used in Geant4. These are classes for run, hit, digit, trajectory and trajectory point, which are discussed in Section 6.2 for G4Run, Section 4.4 for G4VHit, Section 4.5 for G4VDigit, and Section 5.1.6 for G4VTrajectory and G4VTrajectoryPoint
- create concrete classes from provided abstract base classes and associate them with classes used in Geant4. Geant4 classes which can accommodate user information classes are G4Event, G4Track, G4PrimaryVertex, G4PrimaryParticle and G4Region. These classes are discussed here.

6.3.1. G4VUserEventInformation

G4VUserEventInformation is an abstract class from which the user can derive his/her own concrete class for storing user information associated with a G4Event class object. It is the user's responsibility to construct a concrete class object and set the pointer to a proper G4Event object.

Within a concrete implementation of G4UserEventAction, the SetUserEventInformation() method of G4EventManager may be used to set a pointer of a concrete class object to G4Event, given that the G4Event object is available only by "pointer to const". Alternatively, the user may modify the GenerateEvent() method of his/her own RunManager to instantiate a G4VUserEventInformation object and set it to G4Event.

The concrete class object is deleted by the Geant4 kernel when the associated G4Event object is deleted.

6.3.2. G4VUserTrackInformation

This is an abstract class from which the user can derive his/her own concrete class for storing user information associated with a G4Track class object. It is the user's responsibility to construct a concrete class object and set the pointer to the proper G4Track object.

Within a concrete implementation of G4UserTrackingAction, the SetUserTrackInformation() method of G4TrackingManager may be used to set a pointer of a concrete class object to G4Track, given that the G4Track object is available only by "pointer to const".

The ideal place to copy a G4VUserTrackInformation object from a mother track to its daughter tracks is *G4UserTrackingAction::PostUserTrackingAction()*.

Example 6.9. Copying `G4VUserTrackInformation` from mother to daughter tracks

```
void RE01TrackingAction::PostUserTrackingAction(const G4Track* aTrack)
{
  G4TrackVector* secondaries = fpTrackingManager->GimmeSecondaries();
  if(secondaries)
  {
    RE01TrackInformation* info = (RE01TrackInformation*)(aTrack->GetUserInformation());
    size_t nSeco = secondaries->size();
    if(nSeco>0)
    {
      for(size_t i=0; i < nSeco; i++)
      {
        RE01TrackInformation* infoNew = new RE01TrackInformation(info);
        (*secondaries)[i]->SetUserInformation(infoNew);
      }
    }
  }
}
```

The concrete class object is deleted by the Geant4 kernel when the associated G4Track object is deleted. In case the user wants to keep the information, it should be copied to a trajectory corresponding to the track.

6.3.3. G4VUserPrimaryVertexInformation and G4VUserPrimaryTrackInformation

These abstract classes allow the user to attach information regarding the generated primary vertex and primary particle. Concrete class objects derived from these classes should be attached to *G4PrimaryVertex* and *G4PrimaryParticle* class objects, respectively.

The concrete class objects are deleted by the Geant4 Kernel when the associated G4PrimaryVertex or G4PrimaryParticle class objects are deleted along with the deletion of G4Event.

6.3.4. G4VUserRegionInformation

This abstract base class allows the user to attach information associated with a region. For example, it would be quite beneficial to add some methods returning a boolean flag to indicate the characteristics of the region (e.g. tracker, calorimeter, etc.). With this example, the user can easily and quickly identify the detector component.

Example 6.10. A sample region information class

```
class RE01RegionInformation : public G4VUserRegionInformation
{
  public:
    RE01RegionInformation();
    ~RE01RegionInformation();
    void Print() const;

  private:
    G4bool isWorld;
    G4bool isTracker;
    G4bool isCalorimeter;

  public:
    inline void SetWorld(G4bool v=true) {isWorld = v;}
    inline void SetTracker(G4bool v=true) {isTracker = v;}
    inline void SetCalorimeter(G4bool v=true) {isCalorimeter = v;}
    inline G4bool IsWorld() const {return isWorld;}
    inline G4bool IsTracker() const {return isTracker;}
    inline G4bool IsCalorimeter() const {return isCalorimeter;}
};
```

The following code is an example of a stepping action. Here, a track is suspended when it enters the "calorimeter region" from the "tracker region".

Example 6.11. Sample use of a region information class

```
void RE01SteppingAction::UserSteppingAction(const G4Step * theStep)
{
  // Suspend a track if it is entering into the calorimeter

  // check if it is alive
  G4Track * theTrack = theStep->GetTrack();
  if(theTrack->GetTrackStatus()!=fAlive) { return; }

  // get region information
  G4StepPoint * thePrePoint = theStep->GetPreStepPoint();
  G4LogicalVolume * thePreLV = thePrePoint->GetPhysicalVolume()->GetLogicalVolume();
  RE01RegionInformation* thePreRInfo
   = (RE01RegionInformation*)(thePreLV->GetRegion()->GetUserInformation());
  G4StepPoint * thePostPoint = theStep->GetPostStepPoint();
  G4LogicalVolume * thePostLV = thePostPoint->GetPhysicalVolume()->GetLogicalVolume();
  RE01RegionInformation* thePostRInfo
   = (RE01RegionInformation*)(thePostLV->GetRegion()->GetUserInformation());

  // check if it is entering to the calorimeter volume
  if(!(thePreRInfo->IsCalorimeter()) && (thePostRInfo->IsCalorimeter()))
  { theTrack->SetTrackStatus(fSuspend); }
}
```

Chapter 7. Communication and Control

7.1. Built-in Commands

Geant4 has various built-in user interface commands, each of which corresponds roughly to a Geant4 category. These commands can be used

- interactively via a (Graphical) User Interface - (G)UI,
- in a macro file via /control/execute <command>,
- within C++ code with the ApplyCommand method of G4UImanager.

Note

The availability of individual commands, the ranges of parameters, the available candidates on individual command parameters **vary** according to the implementation of your application and may even **vary** dynamically during the execution of your job.

The following is a short summary of available commands. You can also see the all available commands by executeing 'help' in your UI session.

- List of built-in commands

7.2. User Interface - Defining New Commands

7.2.1. G4UImessenger

G4UImessenger is a base class which represents a messenger that delivers command(s) to the destination class object. Your concrete messenger should have the following functionalities.

- Construct your command(s) in the constructor of your messenger.
- Destruct your command(s) in the destructor of your messenger.

These requirements mean that your messenger should keep all pointers to your command objects as its data members.

You can use *G4UIcommand* derived classes for the most frequent types of command. These derived classes have their own conversion methods according to their types, and they make implementation of the `SetNewValue()` and `GetCurrentValue()` methods of your messenger much easier and simpler.

For complicated commands which take various parameters, you can use the *G4UIcommand* base class, and construct *G4UIparameter* objects by yourself. You don't need to delete *G4UIparameter* object(s).

In the `SetNewValue()` and `GetCurrentValue()` methods of your messenger, you can compare the *G4UIcommand* pointer given in the argument of these methods with the pointer of your command, because your messenger keeps the pointers to the commands. Thus, you don't need to compare by command name. Please remember, in the cases where you use *G4UIcommand* derived classes, you should store the pointers with the types of these derived classes so that you can use methods defined in the derived classes according to their types without casting.

G4UImanager/G4UIcommand/G4UIparameter have very powerful type and range checking routines. You are strongly recommended to set the range of your parameters. For the case of a numerical value (`int` or `double`), the range can be given by a *G4String* using C++ notation, e.g., `"X > 0 && X < 10"`. For the case of a string type parameter, you can set a candidate list. Please refer to the detailed descriptions below.

`GetCurrentValue()` will be invoked after the user's application of the corresponding command, and before the `SetNewValue()` invocation. This `GetCurrentValue()` method will be invoked only if

- at least one parameter of the command has a range
- at least one parameter of the command has a candidate list
- at least the value of one parameter is omitted and this parameter is defined as omittable and `currentValueAsDefault`

For the first two cases, you can re-set the range or the candidate list if you need to do so, but these ``re-set'' parameters are needed only for the case where the range or the candidate list varies dynamically.

A command can be ``state sensitive'', i.e., the command can be accepted only for a certain *G4ApplicationState*(s). For example, the `/run/beamOn` command should not be accepted when Geant4 is processing another event (``G4State_EventProc'' state). You can set the states available for the command with the `AvailableForStates()` method.

7.2.2. G4UIcommand and its derived classes

Methods available for all derived classes

These are methods defined in the *G4UIcommand* base class which should be used from the derived classes.

- `void SetGuidance(char*)`

  Define a guidance line. You can invoke this method as many times as you need to give enough amount of guidance. Please note that the first line will be used as a title head of the command guidance.
- `void availableForStates(G4ApplicationState s1,...)`

  If your command is valid only for certain states of the Geant4 kernel, specify these states by this method. Currently available states are `G4State_PreInit, G4State_Init, G4State_Idle, G4State_GeomClosed,` and `G4State_EventProc`. Refer to the section 3.4.2 for meaning of each state. Please note that the `Pause` state had been removed from *G4ApplicationState*.
- `void SetRange(char* range)`

  Define a range of the parameter(s). Use C++ notation, e.g., `"x > 0 && x < 10"`, with variable name(s) defined by the `SetParameterName()` method. For the case of a *G4ThreeVector*, you can set the relation between parameters, e.g., `"x > y"`.

G4UIdirectory

This is a *G4UIcommand* derived class for defining a directory.

- `G4UIdirectory(char* directoryPath)`

  Constructor. Argument is the (full-path) directory, which must begin and terminate with `/'.

G4UIcmdWithoutParameter

This is a *G4UIcommand* derived class for a command which takes no parameter.

- `G4UIcmdWithoutParameter(char* commandPath, G4UImessenger* theMessenger)`

  Constructor. Arguments are the (full-path) command name and the pointer to your messenger.

G4UIcmdWithABool

This is a *G4UIcommand* derived class which takes one boolean type parameter.

- `G4UIcmdWithABool(char* commandpath,G4UImanager* theMessenger)`

  Constructor. Arguments are the (full-path) command name and the pointer to your messenger.
- `void SetParameterName(char* paramName, G4bool omittable)`

Define the name of the boolean parameter and set the omittable flag. If omittable is true, you should define the default value using the next method.

- `void SetDefaultValue(G4bool defVal)`

  Define the default value of the boolean parameter.
- `G4bool GetNewBoolValue(G4String paramString)`

  Convert *G4String* parameter value given by the `SetNewValue()` method of your messenger into boolean.
- `G4String convertToString(G4bool currVal)`

  Convert the current boolean value to *G4String* whichshould be returned by the `GetCurrentValue()` method of your messenger.

G4UIcmdWithAnInteger

This is a *G4UIcommand* derived class which takes one integer type parameter.

- `G4UIcmdWithAnInteger(char* commandpath, G4UImanager* theMessenger)`

  Constructor. Arguments are the (full-path) command name and the pointer to your messenger.
- `void SetParameterName(char* paramName, G4bool omittable)`

  Define the name of the integer parameter and set the omittable flag. If omittable is true, you should define the default value using the next method.
- `void SetDefaultValue(G4int defVal)`

  Define the default value of the integer parameter.
- `G4int GetNewIntValue(G4String paramString)`

  Convert *G4String* parameter value given by the `SetNewValue()` method of your messenger into integer.
- `G4String convertToString(G4int currVal)`

  Convert the current integer value to *G4String*, which should be returned by the `GetCurrentValue()` method of your messenger.

G4UIcmdWithADouble

This is a *G4UIcommand* derived class which takes one double type parameter.

- `G4UIcmdWithADouble(char* commandpath, G4UImanager* theMessenger)`

  Constructor. Arguments are the (full-path) command name and the pointer to your messenger.
- `void SetParameterName(char* paramName, G4bool omittable)`

  Define the name of the double parameter and set the omittable flag. If omittable is true, you should define the default value using the next method.
- `void SetDefaultValue(G4double defVal)`

  Define the default value of the double parameter.
- `G4double GetNewDoubleValue(G4String paramString)`

  Convert *G4String* parameter value given by the `SetNewValue()` method of your messenger into double.
- `G4String convertToString(G4double currVal)`

  Convert the current double value to *G4String* which should be returned by the `GetCurrentValue()` method of your messenger.

G4UIcmdWithAString

This is a *G4UIcommand* derived class which takes one string type parameter.

- `G4UIcmdWithAString(char* commandpath, G4UImanager* theMessenger)`

  Constructor. Arguments are the (full-path) command name and the pointer to your messenger.
- `void SetParameterName(char* paramName, G4bool omittable)`

  Define the name of the string parameter and set the omittable flag. If omittable is true, you should define the default value using the next method.
- `void SetDefaultValue(char* defVal)`

  Define the default value of the string parameter.
- `void SetCandidates(char* candidateList)`

  Define a candidate list which can be taken by the parameter. Each candidate listed in this list should be separated by a single space. If this candidate list is given, a string given by the user but which is not listed in this list will be rejected.

G4UIcmdWith3Vector

This is a *G4UIcommand* derived class which takes one three vector parameter.

- `G4UIcmdWith3Vector(char* commandpath, G4UImanager* theMessenger)`

  Constructor. Arguments are the (full-path) command name and the pointer to your messenger.
- `void SetParameterName(char* paramNamX, char* paramNamY, char* paramNamZ, G4bool omittable)`

  Define the names of each component of the three vector and set the omittable flag. If omittable is true, you should define the default value using the next method.
- `void SetDefaultValue(G4ThreeVector defVal)`

  Define the default value of the three vector.
- `G4ThreeVector GetNew3VectorValue(G4String paramString)`

  Convert the *G4String* parameter value given by the `SetNewValue()` method of your messenger into a *G4ThreeVector*.
- `G4String convertToString(G4ThreeVector currVal)`

  Convert the current three vector to *G4String*, which should be returned by the `GetCurrentValue()` method of your messenger.

G4UIcmdWithADoubleAndUnit

This is a *G4UIcommand* derived class which takes one double type parameter and its unit.

- `G4UIcmdWithADoubleAndUnit(char* commandpath, G4UImanager* theMessenger)`

  Constructor. Arguments are the (full-path) command name and the pointer to your messenger.
- `void SetParameterName(char* paramName, G4bool omittable)`

  Define the name of the double parameter and set the omittable flag. If omittable is true, you should define the default value using the next method.
- `void SetDefaultValue(G4double defVal)`

  Define the default value of the double parameter.

- `void SetUnitCategory(char* unitCategory)`

  Define acceptable unit category.
- `void SetDefaultUnit(char* defUnit)`

  Define the default unit. Please use this method and the `SetUnitCategory()` method alternatively.

- `G4double GetNewDoubleValue(G4String paramString)`

  Convert *G4String* parameter value given by the `SetNewValue()` method of your messenger into double. Please note that the return value has already been multiplied by the value of the given unit.
- `G4double GetNewDoubleRawValue(G4String paramString)`

  Convert *G4String* parameter value given by the `SetNewValue()` method of your messenger into double but without multiplying the value of the given unit.
- `G4double GetNewUnitValue(G4String paramString)`

  Convert *G4String* unit value given by the `SetNewValue()` method of your messenger into double.
- `G4String convertToString(G4bool currVal, char* unitName)`

  Convert the current double value to a *G4String*, which should be returned by the `GetCurrentValue()` method of your messenger. The double value will be divided by the value of the given unit and converted to a string. Given unit will be added to the string.

G4UIcmdWith3VectorAndUnit

This is a *G4UIcommand* derived class which takes one three vector parameter and its unit.

- `G4UIcmdWith3VectorAndUnit(char* commandpath, G4UImanager* theMessenger)`

  Constructor. Arguments are the (full-path) command name and the pointer to your messenger.
- `void SetParameterName(char* paramNamX, char* paramNamY, char* paramNamZ,G4bool omittable)`

  Define the names of each component of the three vector and set the omittable flag. If omittable is true, you should define the default value using the next method.
- `void SetDefaultValue(G4ThreeVector defVal)`

  Define the default value of the three vector.
- `void SetUnitCategory(char* unitCategory)`

  Define acceptable unit category.
- `void SetDefaultUnit(char* defUnit)`

  Define the default unit. Please use this method and the `SetUnitCategory()` method alternatively.
- `G4ThreeVector GetNew3VectorValue(G4String paramString)`

  Convert a *G4String* parameter value given by the `SetNewValue()` method of your messenger into a *G4ThreeVector*. Please note that the return value has already been multiplied by the value of the given unit.
- `G4ThreeVector GetNew3VectorRawValue(G4String paramString)`

  Convert a *G4String* parameter value given by the `SetNewValue()` method of your messenger into three vector, but without multiplying the value of the given unit.
- `G4double GetNewUnitValue(G4String paramString)`

  Convert a *G4String* unit value given by the `SetNewValue()` method of your messenger into a double.
- `G4String convertToString(G4ThreeVector currVal, char* unitName)`

  Convert the current three vector to a *G4String* which should be returned by the `GetCurrentValue()` method of your messenger. The three vector value will be divided by the value of the given unit and converted to a string. Given unit will be added to the string.

Additional comments on the `SetParameterName()` method

You can add one additional argument of `G4bool` type for every `SetParameterName()` method mentioned above. This additional argument is named `currentAsDefaultFlag` and the default value of this argument is

`false`. If you assign this extra argument as `true`, the default value of the parameter will be overriden by the current value of the target class.

7.2.3. An example messenger

This example is of *G4ParticleGunMessenger*, which is made by inheriting *G4UIcommand*.

Example 7.1. An example of `G4ParticleGunMessenger.hh`.

```
#ifndef G4ParticleGunMessenger_h
#define G4ParticleGunMessenger_h 1

class G4ParticleGun;
class G4ParticleTable;
class G4UIcommand;
class G4UIdirectory;
class G4UIcmdWithoutParameter;
class G4UIcmdWithAString;
class G4UIcmdWithADoubleAndUnit;
class G4UIcmdWith3Vector;
class G4UIcmdWith3VectorAndUnit;

#include "G4UImessenger.hh"
#include "globals.hh"

class G4ParticleGunMessenger: public G4UImessenger
{
  public:
    G4ParticleGunMessenger(G4ParticleGun * fPtclGun);
    ~G4ParticleGunMessenger();

  public:
    void SetNewValue(G4UIcommand * command,G4String newValues);
    G4String GetCurrentValue(G4UIcommand * command);

  private:
    G4ParticleGun * fParticleGun;
    G4ParticleTable * particleTable;

  private: //commands
    G4UIdirectory *             gunDirectory;
    G4UIcmdWithoutParameter *   listCmd;
    G4UIcmdWithAString *        particleCmd;
    G4UIcmdWith3Vector *        directionCmd;
    G4UIcmdWithADoubleAndUnit * energyCmd;
    G4UIcmdWith3VectorAndUnit * positionCmd;
    G4UIcmdWithADoubleAndUnit * timeCmd;

};

#endif
```

Example 7.2. An example of `G4ParticleGunMessenger.cc`.

```
#include "G4ParticleGunMessenger.hh"
#include "G4ParticleGun.hh"
#include "G4Geantino.hh"
#include "G4ThreeVector.hh"
#include "G4ParticleTable.hh"
#include "G4UIdirectory.hh"
#include "G4UIcmdWithoutParameter.hh"
#include "G4UIcmdWithAString.hh"
#include "G4UIcmdWithADoubleAndUnit.hh"
#include "G4UIcmdWith3Vector.hh"
#include "G4UIcmdWith3VectorAndUnit.hh"
#include <iostream.h>

G4ParticleGunMessenger::G4ParticleGunMessenger(G4ParticleGun * fPtclGun)
:fParticleGun(fPtclGun)
{
  particleTable = G4ParticleTable::GetParticleTable();

  gunDirectory = new G4UIdirectory("/gun/");
  gunDirectory->SetGuidance("Particle Gun control commands.");

  listCmd = new G4UIcmdWithoutParameter("/gun/list",this);
  listCmd->SetGuidance("List available particles.");
  listCmd->SetGuidance(" Invoke G4ParticleTable.");

  particleCmd = new G4UIcmdWithAString("/gun/particle",this);
  particleCmd->SetGuidance("Set particle to be generated.");
  particleCmd->SetGuidance(" (geantino is default)");
  particleCmd->SetParameterName("particleName",true);
  particleCmd->SetDefaultValue("geantino");
  G4String candidateList;
  G4int nPtcl = particleTable->entries();
  for(G4int i=0;i<nPtcl;i++)
  {
    candidateList += particleTable->GetParticleName(i);
    candidateList += " ";
  }
  particleCmd->SetCandidates(candidateList);

  directionCmd = new G4UIcmdWith3Vector("/gun/direction",this);
  directionCmd->SetGuidance("Set momentum direction.");
  directionCmd->SetGuidance("Direction needs not to be a unit vector.");
  directionCmd->SetParameterName("Px","Py","Pz",true,true);
  directionCmd->SetRange("Px != 0 || Py != 0 || Pz != 0");

  energyCmd = new G4UIcmdWithADoubleAndUnit("/gun/energy",this);
  energyCmd->SetGuidance("Set kinetic energy.");
  energyCmd->SetParameterName("Energy",true,true);
  energyCmd->SetDefaultUnit("GeV");
  energyCmd->SetUnitCandidates("eV keV MeV GeV TeV");

  positionCmd = new G4UIcmdWith3VectorAndUnit("/gun/position",this);
  positionCmd->SetGuidance("Set starting position of the particle.");
  positionCmd->SetParameterName("X","Y","Z",true,true);
  positionCmd->SetDefaultUnit("cm");
  positionCmd->SetUnitCandidates("micron mm cm m km");

  timeCmd = new G4UIcmdWithADoubleAndUnit("/gun/time",this);
  timeCmd->SetGuidance("Set initial time of the particle.");
  timeCmd->SetParameterName("t0",true,true);
  timeCmd->SetDefaultUnit("ns");
  timeCmd->SetUnitCandidates("ns ms s");

  // Set initial value to G4ParticleGun
  fParticleGun->SetParticleDefinition( G4Geantino::Geantino() );
  fParticleGun->SetParticleMomentumDirection( G4ThreeVector(1.0,0.0,0.0) );
  fParticleGun->SetParticleEnergy( 1.0*GeV );
  fParticleGun->SetParticlePosition(G4ThreeVector(0.0*cm, 0.0*cm, 0.0*cm));
  fParticleGun->SetParticleTime( 0.0*ns );
}
```

```
G4ParticleGunMessenger::~G4ParticleGunMessenger()
{
```

```
  delete listCmd;
  delete particleCmd;
  delete directionCmd;
  delete energyCmd;
  delete positionCmd;
  delete timeCmd;
  delete gunDirectory;
}

void G4ParticleGunMessenger::SetNewValue(
  G4UIcommand * command,G4String newValues)
{
  if( command==listCmd )
  { particleTable->dumpTable(); }
  else if( command==particleCmd )
  {
    G4ParticleDefinition* pd = particleTable->findParticle(newValues);
    if(pd != NULL)
    { fParticleGun->SetParticleDefinition( pd ); }
  }
  else if( command==directionCmd )
  { fParticleGun->SetParticleMomentumDirection(directionCmd->
     GetNew3VectorValue(newValues)); }
  else if( command==energyCmd )
  { fParticleGun->SetParticleEnergy(energyCmd->
     GetNewDoubleValue(newValues)); }
  else if( command==positionCmd )
  { fParticleGun->SetParticlePosition(
     directionCmd->GetNew3VectorValue(newValues)); }
  else if( command==timeCmd )
  { fParticleGun->SetParticleTime(timeCmd->
     GetNewDoubleValue(newValues)); }
}

G4String G4ParticleGunMessenger::GetCurrentValue(G4UIcommand * command)
{
  G4String cv;

  if( command==directionCmd )
  { cv = directionCmd->ConvertToString(
     fParticleGun->GetParticleMomentumDirection()); }
  else if( command==energyCmd )
  { cv = energyCmd->ConvertToString(
     fParticleGun->GetParticleEnergy(),"GeV"); }
  else if( command==positionCmd )
  { cv = positionCmd->ConvertToString(
     fParticleGun->GetParticlePosition(),"cm"); }
  else if( command==timeCmd )
  { cv = timeCmd->ConvertToString(
     fParticleGun->GetParticleTime(),"ns"); }
  else if( command==particleCmd )
  { // update candidate list
    G4String candidateList;
    G4int nPtcl = particleTable->entries();
    for(G4int i=0;i<nPtcl;i++)
    {
      candidateList += particleTable->GetParticleName(i);
      candidateList += " ";
    }
    particleCmd->SetCandidates(candidateList);
  }
  return cv;
}
```

7.2.4. How to control the output of G4cout/G4cerr

Instead of *cout* and *cerr*, Geant4 uses *G4cout* and *G4cerr*. Output streams from *G4cout/G4cerr* are handled by *G4UImanager* which allows the application programmer to control the flow of the stream. Output strings may therefore be displayed on another window or stored in a file. This is accomplished as follows:

1. Derive a class from *G4UIsession* and implement the two methods:

```
      G4int ReceiveG4cout(G4String coutString);
      G4int ReceiveG4cerr(G4String cerrString);
```

These methods receive the string stream of *G4cout* and *G4cerr*, respectively. The string can be handled to meet specific requirements. The following sample code shows how to make a log file of the output stream:

```
ostream logFile;
logFile.open("MyLogFile");
G4int MySession::ReceiveG4cout(G4String coutString)
{
  logFile << coutString << flush;
  return 0;
}
```

2. Set the destination of *G4cout/G4cerr* using `G4UImanager::SetCoutDestination(session)`.

   Typically this method is invoked from the constructor of *G4UIsession* and its derived classes, such as *G4UIGAG/G4UIteminal*. This method sets the destination of *G4cout/G4cerr* to the session. For example, when the following code appears in the constructor of *G4UIterminal*, the method `SetCoutDestination(this)` tells *UImanager* that this instance of *G4UIterminal* receives the stream generated by *G4cout*.

```
G4UIterminal::G4UIterminal()
{
  UI = G4UImanager::GetUIpointer();
  UI->SetCoutDestination(this);
  //  ...
}
```

   Similarly, `UI->SetCoutDestination(NULL)` must be added to the destructor of the class.
3. Write or modify the main program. To modify `exampleN01` to produce a log file, derive a class as described in step 1 above, and add the following lines to the main program:

```
#include "MySession.hh"
main()
{
  // get the pointer to the User Interface manager
  G4UImanager* UI = G4UImanager::GetUIpointer();
  // construct a session which receives G4cout/G4cerr
  MySession * LoggedSession = new MySession;
  UI->SetCoutDestination(LoggedSession);
  // session->SessionStart(); // not required in this case
  // .... do simulation here ...

  delete LoggedSession;
  return 0;
}
```

Note

G4cout/G4cerr should not be used in the constructor of a class if the instance of the class is intended to be used as `static`. This restriction comes from the language specification of C++. See the documents below for details:

- M.A.Ellis, B.Stroustrup, ``Annotated C++ Reference Manual'', Section 3.4 [Ellis1990]
- P.J.Plauger, ``The Draft Standard C++ Library'' [Plauger1995]

Chapter 8. Visualization

8.1. Introduction to Visualization

The Geant4 visualization system was developed in response to a diverse set of requirements:

1. Quick response to study geometries, trajectories and hits
2. High-quality output for publications
3. Flexible camera control to debug complex geometries
4. Tools to show volume overlap errors in detector geometries
5. Interactive picking to get more information on visualized objects

No one graphics system is ideal for all of these requirements, and many of the large software frameworks into which Geant4 has been incorporated already have their own visualization systems, so Geant4 visualization was designed around an abstract interface that supports a diverse family of graphics systems. Some of these graphics systems use a graphics library compiled with Geant4, such as OpenGL, Qt, while others involve a separate application, such as HepRApp or DAWN.

8.1.1. What Can be Visualized

Simulation data can be visualized:

- Detector components
  - A hierarchical structure of physical volumes
  - A piece of physical volume, logical volume, and solid
- Particle trajectories and tracking steps
- Hits of particles in detector components

Other user defined objects can be visualized:

- Polylines, such as coordinate axes
- 3D Markers, such as eye guides
- Text, descriptive character strings, comments or titles
- Scales
- Logos

8.1.2. You have a Choice of Visualization Drivers

The many graphics systems that Geant4 supports are complementary to each other.

- OpenGL
  - View directly from Geant4
  - Requires addition of GL libraries that are freely avialable for all operating systems (and pre-installed on many)
  - Rendered, photorealistic image with some interactive features
  - zoom, rotate, translate
  - Fast response (can usually exploit full potential of graphics hardware)
  - Print to EPS (vector and pixel graphics)
- Qt
  - View directly from Geant4
  - Requires addition of Qt and GL libraries that are freely available on most operating systems
  - Rendered, photorealistic image
  - Many interactive features
  - zoom, rotate, translate
  - Fast response (can usually exploit full potential of graphics hardware)
  - Expanded printing ability (vector and pixel graphics)

    - Easy interface to make movies
- OpenInventor
    - View directly from Geant4
    - Requires addition of OpenInventor libraries (freely available for most Linux systems).
    - Rendered, photorealistic image
    - Many interactive features
    - zoom, rotate, translate
    - click to "see inside" opaque volumes
    - Fast response (can usually exploit full potential of graphics hardware)
    - Expanded printing ability (vector and pixel graphics)
- HepRep
    - Create a file to view in a HepRep browser such as HepRApp, FRED or WIRED4
    - Requires a HepRep browser (above options work on any operating system)
    - Wireframe or simple area fills (not photorealistic)
    - Many interactive features
    - zoom, rotate, translate
    - click to show attributes (momentum, etc.)
    - special projections (FishEye, etc.)
    - control visibility from hierarchical (tree) view of data
    - Hierarchical view of the geometry
    - Export to many vector graphic formats (PostScript, PDF, etc.)
- DAWN
    - Create a file to view in the DAWN Renderer
    - Requires DAWN, available for all Linux and Windows systems.
    - Rendered, photorealistic image
    - No interactive features
    - Highest quality technical rendering - output to vector PostScript
- VRML
    - Create a file to view in any VRML browser (some as web browser plug-ins).
    - Requires VRML browser (many different choices for different operating systems).
    - Rendered, photorealistic image with some interactive features
    - zoom, rotate, translate
    - Limited printing ability (pixel graphics, not vector graphics)
- RayTracer
    - Create a jpeg file
    - Forms image by using Geant4's own tracking to follow photons through the detector
    - Can show geometry but not trajectories
    - Can render any geometry that Geant4 can handle (such as Boolean solids)
    - Supports shadows, transparency and mirrored surfaces
- ASCIITree
    - Text dump of the geometry hierarchy
    - Not graphical
    - Control over level of detail to be dumped
    - Can calculate mass and volume of any hierarchy of volumes

8.1.3. Choose the Driver that Meets Your Needs

- If you want very responsive photorealistic graphics (and have the OpenGL libraries installed)
    - OpenGL is a good solution (if you have the Motif extensions, this also gives GUI control)
- If you want very responsive photorealistic graphics plus more interactivity (and have the OpenInventor or Qt libraries installed)
    - OpenInventor or Qt are good solutions
- If you want GUI control, very responsive photorealistic graphics plus more interactivity (and have the Qt libraries installed).
    - Qt is a good solution
- If you want GUI control, want to be able to pick on items to inquire about them (identity, momentum, etc.), perhaps want to render to vector formats, and a wireframe look will do

  - HepRep will meet your needs
- If you want to render highest quality photorealistic images for use in a poster or a technical design report, and you can live without quick rotate and zoom
  - DAWN is the way to go
- If you want to render to a 3D format that others can view in a variety of commodity browsers (including some web browser plug-ins)
  - VRML is the way to go

- If you want to visualize a geometry that the other visualization drivers can't handle, or you need transparency or mirrors, and you don't need to visualize trajectories
  - RayTracer will do it
- If you just want to quickly check the geometry hierarchy, or if you want to calculate the volume or mass of any geometry hierarchy
  - ASCIITree will meet your needs
- You can also add your own visualization driver.
  - Geant4's visualization system is modular. By creating just three new classes, you can direct Geant4 information to your own visualization system.

8.1.4. Controlling Visualization

Your Geant4 code stays basically the same no matter which driver you use.

Visualization is performed either with commands or from C++ code.

- Some visualization drivers work directly from Geant4
  - OpenGL
  - Qt
  - OpenInventor
  - RayTracer
  - ASCIITree
- For other visualization drivers, you first have Geant4 produce a file, and then you have that file rendered by another application (which may have GUI control)
  - HepRep
  - DAWN
  - VRML

8.1.5. Visualization Details

The following sections of this guide cover the details of Geant4 visualization:

- Section 8.2 Adding Visualization to Your Executable
- Section 8.3 The Visualization Drivers
- Section 8.4 Controlling Visualization from Commands
- Section 8.5 Controlling Visualization from Compiled Code
- Section 8.6 Visualization Attributes
- Section 8.7 Enhanced Trajectory Drawing
- Section 8.9 Polylines, Markers and Text
- Section 8.10 Making a Movie

Other useful references for Geant4 visualization outside of this user guide:

- Introduction to Geant4 Visualization (pdf, ppt)
- Geant4 Visualization Commands (pdf, ppt)
- Geant4 Advanced Visualization (pdf, ppt)

- How to Make a Movie (pdf, ppt)
- Geant4 Visualization Tutorial using the HepRApp HepRep Browser
- Geant4 Visualization Tutorial using the OpenGL Event Display
- Geant4 Visualization Tutorial using the DAWN Event Display
- Macro files distributed in Geant4 source in `examples/novice/N03/visTutor/`.

8.2. Adding Visualization to Your Executable

This section explains how to incorporate your selected visualization drivers into the `main()` function and create an executable for it. In order to perform visualization with your Geant4 executable, you must compile it with realized visualization driver(s). You may be dazzled by the number of choices of visualization driver, but you need not use all of them at one time.

8.2.1. Installing Visualization Drivers

Depending on what has been installed on your system, several kinds of visualization driver are available. One or many drivers may be chosen for realization in compilation, depending on your visualization requirements. Features and notes on each driver are briefly described in Section 8.3 "**Visualization Drivers**", along with links to detailed web pages for the various drivers.

Note that not all drivers can be installed on all systems; Table 8.1 in Section 8.3 lists all the available drivers and the platforms on which they can be installed. For any of the visualization drivers to work, the corresponding graphics system must be installed beforehand.

Unless the environment variable `G4VIS_NONE` is set to "1", visualization drivers that do not depend on external libraries are automatically incorporated into Geant4 libraries during their installation. (Here "installation of Geant4 libraries" means the generation of Geant4 libraries by compilation.) The automatically incorporated visualization drivers are: DAWNFILE, HepRepFile, HepRepXML, RayTracer, VRML1FILE, VRML2FILE and ATree and GAGTree.

The OpenGL, Qt, OpenInventor and RayTracerX drivers are not incorporated by default. Nor are the DAWN-Network and VRML-Network drivers, because they require the network setting of the installed machine. In order to incorporate them, the environment variables "`G4VIS_BUILD_DRIVERNAME_DRIVER`" should be set to "`1`" before installing the Geant4 libraries:

```
setenv G4VIS_BUILD_OPENGLX_DRIVER      1  # OpenGL-Xlib driver
setenv G4VIS_BUILD_OPENGLXM_DRIVER     1  # OpenGL-Motif driver
setenv G4VIS_BUILD_OPENGLQT_DRIVER     1  # Qt driver
setenv G4VIS_BUILD_OIX_DRIVER          1  # OpenInventor-Xlib driver
setenv G4VIS_BUILD_RAYTRACERX_DRIVER   1  # RayTracer-XLib driver
setenv G4VIS_BUILD_DAWN_DRIVER         1  # DAWN-Network driver
setenv G4VIS_BUILD_VRML_DRIVER         1  # VRML-Network
```

Unless the environment variable `G4VIS_NONE` is set to "1", setting any of the above variables sets a C-pre-processor flag of the same name. Also the C-pre-processor flag `G4VIS_BUILD` is set (see config/G4VIS_BUILD.gmk), which incorparates the selected driver into the Geant4 libraries.

8.2.2. How to Realize Visualization Drivers in an Executable

You can realize and use any of the visualization driver(s) you want in your Geant4 executable, provided they are among the set installed beforehand into the Geant4 libraries. A warning will appear if this is not the case.

In order to realize visualization drivers, you must instantiate and initialize a subclass of `G4VisManager` that implements the pure virtual function `RegisterGraphicsSystems()`. This subclass must be compiled in the user's domain to force the loading of appropriate libraries in the right order. The easiest way to do this is to

use G4VisExecutive, a provided class with included implementation. G4VisExecutive is sensitive to the G4VIS_USE... variables mentioned below.

If you do wish to write your own subclass, you may do so. You will see how to do this by looking at G4VisExecutive.icc. A typical extract is:

```
...
  RegisterGraphicsSystem (new G4DAWNFILE);
...
#ifdef G4VIS_USE_OPENGLX
  RegisterGraphicsSystem (new G4OpenGLImmediateX);
  RegisterGraphicsSystem (new G4OpenGLStoredX);
#endif
...
```

If you wish to use G4VisExecutive but register an additional graphics system, XXX say, you may do so either before or after initializing:

```
visManager->RegisterGraphicsSytem(new XXX);
visManager->Initialize();
```

By default, you get the DAWNFILE, HepRepFile, RayTracer, VRML1FILE, VRML2FILE, ATree and GAGTree drivers. Additionally, you may choose from the OpenGL-Xlib, OpenGL-Motif, Qt, OpenInventor, RayTracerX, DAWN-Network and VRML-Network drivers, each of which can be selected by setting the proper environment variable:

```
setenv G4VIS_USE_OPENGLX      1
setenv G4VIS_USE_OPENGLXM     1
setenv G4VIS_USE_OPENGLQT     1
setenv G4VIS_USE_OIX          1
setenv G4VIS_USE_RAYTRACERX   1
setenv G4VIS_USE_DAWN         1
setenv G4VIS_USE_VRML         1
```

(Of course, this has to be chosen from the set incorporated into the Geant4 libraries during their compilation.) Unless the environment variable G4VIS_NONE is set, these set C-pre-processor flags of the same name.

Also, unless the environment variable G4VIS_NONE is set, the C-pre-processor flag G4VIS_USE is always set by default. This flag is available in describing the main() function.

You may have to set additional environment variables for your selected visualization drivers and graphics systems. For example, the OpenGL driver may require the setting of OGLHOME which points to the location of the OpenGL libraries. For more details, see Section 8.3 "**Visualization Drivers**" and pages linked from there.

8.2.3. A Sample Set-up File

The following can be part of the user's .cshrc or .tcshrc file on a Linux platform to configure the environment for creating Geant4 executables available for Geant4 visualization. This sample is shown only as an example; it may NOT correspond to a specific platform configuration and does NOT apply in general for any specific setup !

Example 8.1. Part of a sample `.cshrc` setup file for the Linux platform.

```
############################################################
# Main Environment Variables for GEANT4 with Visualization #
############################################################

### Platform
setenv G4SYSTEM Linux-g++

### CLHEP base directory
setenv CLHEP_BASE_DIR /opt/local

### OpenGL base directory
setenv OGLHOME /usr/X11R6

### G4VIS_BUILD
###   Incorporation of OpenGL-Xlib and OpenGL-Motif drivers
###   into Geant4 libraries.
setenv G4VIS_BUILD_OPENGLX_DRIVER 1
setenv G4VIS_BUILD_OPENGLXM_DRIVER 1

### G4VIS_USE
###   Incorporation of OpenGL-Xlib and OpenGL-Motif drivers
###   into Geant4 executables.
setenv G4VIS_USE_OPENGLX       1
setenv G4VIS_USE_OPENGLXM      1

### Viewer for DAWNFILE driver
### Default value is "dawn".  You can change it to, say,
### "david" for volume overlapping tests
# setenv G4DAWNFILE_VIEWER david

### Viewer for VRMLFILE drivers
setenv G4VRMLFILE_VIEWER vrmlview

########## end
```

8.2.4. Visualization Manager

Visualization procedures are controlled by the "Visualization Manager", a class which must inherit from *G4VisManager* defined in the visualization category. Most users will find that they can just use the default visualization manager, *G4VisExecutive*. The Visualization Manager accepts users' requests for visualization, processes them, and passes the processed requirements to the abstract interface, i.e., to the currently selected visualization driver.

8.2.5. How to Write the `main()` Function

In order for your Geant4 executable to perform visualization, you must instantiate and initialize "your" Visualization Manager in the `main()` function. The core of the Visualization Manager is the class `G4VisManager`, defined in the visualization category. This class requires that one pure virtual function be implemented, namely, `void RegisterGraphicsSystems()`. The easiest way to do this is to use `G4VisExecutive`, as described above (but you may write your own class - see above).

Example 8.2 shows the form of the `main()` function.

Example 8.2. The form of the `main()` function.

```
//----- C++ source codes: Instantiation and initialization of G4VisManager

.....
// Your Visualization Manager
#include "G4VisExecutive.hh"
.....

// Instantiation and initialization of the Visualization Manager
#ifdef G4VIS_USE
G4VisManager* visManager = new G4VisExecutive;
visManager -> initialize ();
#endif

.....
#ifdef G4VIS_USE
delete visManager;
#endif

//----- end of C++
```

Alternatively, you can implement an empty `RegisterGraphicsSystems()` function, and register visualization drivers you want directly in your `main()` function. See Example 8.3.

Example 8.3. An alternative style for the `main()` function.

```
//----- C++ source codes: How to register a visualization driver directly
//                       in main() function

.....
G4VisManager* visManager = new G4VisExecutive;
visManager -> RegisterGraphicsSystem (new MyGraphicsSystem);
.....
delete visManager

//----- end of C++
```

Do not forget to delete the instantiated Visualization Manager by yourself. Note that a graphics system for Geant4 Visualization may run as a different process. In that case, the destructor of `G4VisManager` might have to terminate the graphics system and/or close the connection.

We recommend that the instantiation, initialization, and deletion of the Visualization Manager be protected by C-pre-processor commands, as in the novice examples. The C-pre-processor macro `G4VIS_USE` is automatically defined unless the environment variable `G4VIS_NONE` is set. This assumes that you are compiling your Geant4 executable with the standard version of GNUmakefile found in the `config` directory.

Example 8.4 shows an example of the `main()` function available for Geant4 Visualization.

Example 8.4. An example of the `main()` function available for Geant4 Visualization.

```
//----- C++ source codes: An example of main() for visualization
.....
#include "G4VisExecutive.hh"
.....

int main()
{
     // Run Manager
     G4RunManager * runManager = new G4RunManager;

     // Detector components
     runManager->set_userInitialization(new MyDetectorConstruction);
     runManager->set_userInitialization(new MyPhysicsList);

     // UserAction classes.
     runManager->set_userAction(new MyRunAction);
     runManager->set_userAction(new MyPrimaryGeneratorAction);
     runManager->set_userAction(new MyEventAction);
     runManager->set_userAction(new MySteppingAction);

#ifdef G4VIS_USE
     G4VisManager* visManager = new G4VisExecutive;
     visManager -> initialize ();
#endif

     // Event loop
     // Define (G)UI terminal
     G4UIsession * session = new G4UIterminal
     session->SessionStart();

     delete session;
     delete runManager;

#ifdef G4VIS_USE
     delete visManager;
#endif

     return 0;
}

//----- end of C++
```

Useful information on incorporated visualization drivers can be displayed in initializing the Visualization Manager. This is done by setting the verbosity flag to an appropriate string:

```
  Simple graded message scheme - give first letter or a digit:
   0) quiet,         // Nothing is printed.
   1) startup,       // Startup and endup messages are printed...
   2) errors,        // ...and errors...
   3) warnings,      // ...and warnings...
   4) confirmations, // ...and confirming messages...
   5) parameters,    // ...and parameters of scenes and views...
   6) all            // ...and everything available.
```

For example, in your `main()` function, write the following code:

```
 ...
 G4VisManager* visManager = new G4VisExecutive ();
 visManager -> SetVerboseLevel (1);
 visManager -> Initialize ();
 ...
```

(This can also be set with the `/vis/verbose` command.)

8.3. The Visualization Drivers

As explained in the Introduction to Visualization , Geant4 provides many different choices of visualization systems. Features and notes on each driver are briefly described here along with links to detailed web pages for the various drivers.

Details are given below for:

- Section 8.3.2 OpenGL
- Section 8.3.3 Qt
- Section 8.3.4 OpenInventor
- Section 8.3.5 HepRepFile
- Section 8.3.6 HepRepXML
- Section 8.3.7 DAWN
- Section 8.3.9 VRML
- Section 8.3.10 RayTracer
- Section 8.3.11 gMocren
- Section 8.3.12 ASCIITree
- Section 8.3.13 GAGTree
- Section 8.3.14 XMLTree

8.3.1. Availability of drivers on the supported systems

Table 8.1 lists required graphics systems and supported platforms for the various visualization drivers

Driver	Required Graphics System	Platform
OpenGL-Xlib	OpenGL	Linux, UNIX, Mac with Xlib
OpenGL-Motif	OpenGL	Linux, UNIX, Mac with Motif
OpenGL-Win32	OpenGL	Windows
Qt	Qt, OpenGL	Linux, UNIX, Mac, Windows
OpenInventor-X	OpenInventor, OpenGL	Linux, UNIX, Mac with Xlib or Motif
OpenInventor-Win32	OpenInventor, OpenGL	Windows
HepRep	HepRApp, FRED or WIRED4 HepRep Browser	Linux, UNIX, Mac, Windows
DAWNFILE	Fukui Renderer DAWN	Linux, UNIX, Mac, Windows
DAWN-Network	Fukui Renderer DAWN	Linux, UNIX
VRMLFILE	any VRML viewer	Linux, UNIX, Mac, Windows
VRML-Network	any network-enabled VRML viewer	Linux, UNIX
RayTracer	any JPEG viewer	Linux, UNIX, Mac, Windows
ASCIITree	none	Linux, UNIX, Mac, Windows
GAGTree	GAG	Linux, UNIX, Mac, Windows
XMLTree	any XML viewer	Linux, UNIX, Mac, Windows

Table 8.1. Required graphics systems and supported platforms for the various visualization drivers.

8.3.2. OpenGL

These drivers have been developed by John Allison and Andrew Walkden (University of Manchester). It is an interface to the de facto standard 3D graphics library, OpenGL. It is well suited for real-time fast visualization and demonstration. Fast visualization is realized with hardware acceleration, reuse of shapes stored in a display list, etc. NURBS visualization is also supported.

Several versions of the OpenGL drivers are prepared. Versions for Xlib, Motif and Win32 platforms are available by default. For each version, there are two modes: immediate mode and stored mode. The former has no limitation on data size, and the latter is fast for visualizing large data repetitively, and so is suitable for animation.

Output can be exported to EPS (both vector and pixel graphics) using vis/ogl/printEPS.

More information can be found here : Section 8.4.13

If you don't have Motif or Qt, all control is done from Geant4 commands:

```
    /vis/open OGLIX
    /vis/viewer/set/viewpointThetaPhi 70 20
    /vis/viewer/zoom 2
    etc.
```

But if you have Motif libraries, you can control Geant4 from Motif widgets:

```
    /vis/open OGLIXm
```

If you have Qt, see the Qt section below.

The OpenGL driver added Smooth shading and Transparency since Geant4 release 8.0.

Further information (OpenGL and Mesa):

- http://www.opengl.org/
- http://www.mesa3d.org
- http://geant4.slac.stanford.edu/Presentations/vis/G4OpenGLTutorial/G4OpenGLTutorial.html using the OpenGL Graphics System

8.3.3. Qt

This driver has been developed by Laurent Garnier (IN2P3, LAL Orsay). It is an interface to the powerful application framework, Qt, now free on most platforms. This driver also requires the OpenGL library.

The Qt driver is well suited for real-time fast visualization and demonstration. Fast visualization is realized with hardware acceleration, reuse of shapes stored in a display list, etc. NURBS visualization is also supported. All OpenGL features are implemented in the Qt driver, but one also gets mouse control of rotation/translation/zoom, the ability to save your scene in many formats (both vector and pixel graphics) and an easy interface for making movies.

Two display modes are available: immediate mode and stored mode. The former has no limitation on data size, and the latter is fast for visualizing large data repetitively, and so is suitable for animation.

To see the visualization window :

```
    /vis/open OGLSQt  (for Stored mode)
or
    /vis/open OGLIQt  (for Immediate mode)
```

Further information (Qt):

- Qt
- Geant4 Visualization Tutorial using the Qt Driver

8.3.4. OpenInventor

These drivers were developed by Jeff Kallenbach (FNAL) and Guy Barrand (IN2P3) based on the Hepvis class library originated by Joe Boudreau (Pittsburgh University). The OpenInventor drivers and the Hepvis class library are based on the well-established OpenInventor technology for scientific visualization. They have high extendibility. They support high interactivity, e.g., attribute e diting of picked objects. Some OpenInventor viewers support "stereoscopic" effects.

It is also possible to save a visualized 3D scene as an OpenInventor-formatted file, and re-visualize the scene afterwards.

Because it is connected directly to the Geant4 kernel, using same language as that kernel (C++), OpenInventor systems can have direct access to Geant4 data (geometry, trajectories, etc.).

Because OpenInventor uses OpenGL for rendering, it supports lighting and transparency.

OpenInventor provides thumbwheel control to rotate and zoom.

OpenInventor supports picking to ask about data. [Control Clicking] on a volume turns on rendering of that volume's daughters. [Shift Clicking] a daughter turns that rendering off: If modeling opaque solid, effect is like opening a box to look inside.

Further information (HEPVis and OpenScientist):

- Geant4 Inventor Visualization with OpenScientist http://openscientist.lal.in2p3.fr/v15r0/html/osc_g4_vis_ui.html
- Overall OpenScientist Home http://openscientist.lal.in2p3.fr/v15r0/html/osc_g4_vis_ui.html
- HEPVis http://www-pat.fnal.gov/graphics/HEPVis/www

Further information (OpenInventor):

- http://oss.sgi.com/projects/inventor
- Josie Wernecke, "The Inventor Mentor", Addison Wesley (ISBN 0-201-62495-8)
- Josie Wernecke, "The Inventor Toolmaker", Addison Wesley (ISBN 0-201-62493-1)
- "The Open Inventor C++ Reference Manual", Addison Wesley (ISBN 0-201-62491-5)

8.3.5. HepRepFile

The HepRepFile driver creates a HepRep XML file in the HepRep1 format suitable for viewing with the HepRApp HepRep Browser.

The HepRep graphics format is further described at http://www.slac.stanford.edu/~perl/heprep .

To write just the detector geometry to this file, use the command:

```
/vis/viewer/flush
```

Or, to also include trajectories and hits (after the appropriate /vis/viewer/add/trajectories or /vis/viewer/add/hits commands), just issue:

```
/run/beamOn 1
```

HepRepFile will write a file called G4Data0.heprep to the current directory. Each subsequent file will have a file name like G4Data1.heprep, G4Data2.heprep, etc.

View the file using the HepRApp HepRep Browser, available from:

http://www.slac.stanford.edu/~perl/HepRApp/ .

HepRApp allows you to pick on volumes, trajectories and hits to find out their associated HepRep Attributes, such as volume name, particle ID, momentum, etc. These same attributes can be displayed as labels on the relevant objects, and you can make visibility cuts based on these attributes ("show me only the photons", or "omit any volumes made of iron").

HepRApp can read heprep files in zipped format as well as unzipped, so you can save space by applying gzip to the heprep file. This will reduce the file to about five percent of its original size.

Several commands are available to override some of HepRepFile's defaults

- You can specify a different directory for the heprep output files by using the setFileDir command, as in:

```
/vis/heprep/setFileDir <someOtherDir/someOtherSubDir>
```

- You can specify a different file name (the part before the number) by using the setFileName command, as in:

```
/vis/heprep/setFileName <my_file_name>
```

  which will produce files named <my_file_name>0.heprep, <my_file_name>1.heprep, etc.
- You can specify that each file should overwrite the previous file (always rewriting to the same file name) by using the setOverwrite command, as in:

```
/vis/heprep/setOverwrite true
```

  This may be useful in some automated applications where you always want to see the latest output file in the same location.

- Geant4 visualization supports a concept called "culling", by which certain parts of the detector can be made invisible. Since you may want to control visibility from the HepRep browser, turning on visibility of detector parts that had defaulted to be invisible, the HepRepFile driver does not omit these invisible detector parts from the HepRep file. But for very large files, if you know that you will never want to make these parts visible, you can choose to have them left entirely out of the file. Use the /vis/heprep/setCullInvisibles command, as in:

```
/vis/heprep/setCullInvisibles true
```

Further information:

- HepRApp Users Home Page:

  http://www.slac.stanford.edu/~perl/HepRApp/ .
- HepRep graphics format:

  http://www.slac.stanford.edu/~perl/heprep
- Geant4 Visualization Tutorial using the HepRApp HepRep Browser

  http://geant4.slac.stanford.edu/Presentations/vis/G4HepRAppTutorial/G4HepRAppTutorial.html

8.3.6. HepRepXML

The HepRepXML driver creates a HepRep file in the HepRep2 format suitable for viewing with the WIRED4 Plugin to the JAS3 Analysis System or the FRED event display.

This driver can write both Binary HepRep (.bheprep) and XML HepRep (.heprep) files. Binary HepRep files are a one-to-one translation of XML HepRep files, but they are considerably shorter and faster to parse by a HepRepViewer such as WIRED 4.

Both Binary HepRep and XML HepRep can be compressed using the standard zlib library if linked into Geant4 using G4LIB_USE_ZLIB. If a standard zlib is not available (WIN32-VC for instance) you should also set G4LIB_BUILD_ZLIB to build G4zlib included with Geant4.

HepRep files (Binary and XML) can contain multiple HepRep events/geometries. If the file contains more than one HepRep it is not strictly XML anymore. Files can be written in .heprep.zip, .heprep.gz or .heprep format and their binary versions .bheprep.zip, .bheprep.gz or .bheprep.

The .heprep.zip is the default for file output, the .heprep is the default for stdout and stderr.

(Optional) To set the filename with a particular extension such as: .heprep.zip, .heprep.gz, .heprep, .bheprep.zip, .bheprep.gz or .bheprep use for instance:

```
/vis/scene/create filename.bheprep.zip
```

(Optional) To create separate files for each event, you can set a suffix such as "-0001" to start writing files from filename-0001.bheprep.zip to filename-9999.bheprep.zip (or up), while "-55-sub" will start write files filename-55-sub.bheprep.zip to filename-99-sub.bheprep.zip (or up).

```
/vis/heprep/setEventNumberSuffix -0001
```

(Note: suffix has to contain at least one digit)

(Optional) To route the HepRep XML output to stdout (or stderr), by default uncompressed, use:

```
/vis/scene/create stdout
```

(Optional) To add attributes to each point on a trajectory, use:

```
/vis/heprep/addPointAttributes 1
```

Be aware that this may increase the size of the output dramatically.

(Optional) You may use the commands:

```
/vis/viewer/zoom                          to set an initial zoom factor

/vis/viewer/set/viewpointThetaPhi         to set an initial view point

/vis/heprep/setCoordinateSystem uvw       to change the coordinate system, where uvw
                                          can be "xyz", "zxy", ...
```

(Optional) You may decide to write .zip files with events and geometry separated (but linked). This results in a smaller zip file, as the geometry is only written once. Use the command:

```
/vis/heprep/appendGeometry false
```

(Optional) To close the file, remove the SceneHandler, use:

```
/vis/sceneHandler/remove scene-handler-0
```

Limitations: Only one SceneHandler can exist at any time, connected to a single Viewer. Since the HepRep format is a model rather than a view this is not a real limitation. In WIRED 4 you can create as many views (SceneHandlers) as you like.

Further information:

- WIRED4 Plugin to the JAS3 Analysis System
- FRED event display
- HepRep graphics format:

  http://www.slac.stanford.edu/~perl/heprep

8.3.7. DAWN

The DAWN drivers are interfaces to Fukui Renderer DAWN, which has been developed by Satoshi Tanaka, Minato Kawaguti et al (Fukui University). It is a vectorized 3D PostScript processor, and so well suited to prepare technical high quality outputs for presentation and/or documentation. It is also useful for precise debugging of detector geometry. Remote visualization, off-line re-visualization, cut view, and many other useful functions of detector simulation are supported. A DAWN process is automatically invoked as a co-process of Geant4 when visualization is performed, and 3D data are passed with inter-process communication, via a file, or the TCP/IP socket.

When Geant4 Visualization is performed with the DAWN driver, the visualized view is automatically saved to a file named `g4.eps` in the current directory, which describes a vectorized (Encapsulated) PostScript data of the view.

There are two kinds of DAWN drivers, the DAWNFILE driver and the DAWN-Network driver. The DAWNFILE driver is usually recommended, since it is faster and safer in the sense that it is not affected by network conditions.

The DAWNFILE driver sends 3D data to DAWN via an intermediate file, named `g4.prim` in the current directory. The file `g4.prim` can be re-visualized later without the help of Geant4. This is done by invoking DAWN by hand:

```
% dawn g4.prim
```

DAWN files can also serve as input to two additional programs:

- A standalone program, DAWNCUT, can perform a planar cut on a DAWN image. DAWNCUT takes as input a .prim file and some cut parameters. Its output is a new .prim file to which the cut has been applied.
- Another standalone program, DAVID, can show you any volume overlap errors in your geometry. DAVID takes as input a .prim file and outputs a new .prim file in which overlapping volumes have been highlighted. The use of DAVID is described in section Section 4.1.11 of this manual.

The DAWN-Network driver is almost the same as the DAWNFILE driver except that

- 3D data are passed to DAWN via the TCP/IP the socket (default) or the named pipe, and that,

If you have not set up network configurations of your host machine, set the environment variable `G4DAWN_NAMED_PIPE` to "1", e.g., `% setenv G4DAWN_NAMED_PIPE 1`. This setting switches the default socket connection to the named-pipe connection within the same host machine. The DAWN-Network driver also saves the 3D data to the file `g4.prim` in the current directory.

8.3.8. Remote Visualization with the DAWN-Network Driver

Visualization in Geant4 is considered to be "remote" when it is performed on a machine other than the Geant4 host. Some of the visualization drivers support this feature.

Usually, the visualization host is your local host, while the Geant4 host is a remote host where you log in, for example, with the `telnet` command. This enables distributed processing of Geant4 visualization, avoiding the transfer of large amounts of visualization data to your terminal display via the network. This section describes how to perform remote Geant4 visualization with the DAWN-Network driver. In order to do it, you must install the Fukui Renderer DAWN on your local host beforehand.

The following steps realize remote Geant4 visualization viewed by DAWN.

1. Invoke DAWN with "-G" option on your local host:

```
Local_Host> dawn -G
```

This invokes DAWN with the network connection mode.

2. Login to the remote host where a Geant4 executable is placed.
3. Set an environment variable on the remote host as follows:

```
Remote_Host> setenv G4DAWN_HOST_NAME local_host_name
```

For example, if you are working in the local host named "arkoop.kek.jp", set this environment variable as follows:

```
Remote_Host> setenv G4DAWN_HOST_NAME arkoop.kek.jp
```

This tells a Geant4 process running on the remote host where Geant4 Visualization should be performed, i.e., where the visualized views should be displayed.

4. Invoke a Geant4 process and perform visualization with the DAWN-Network driver. For example:

```
Idle> /vis/open DAWN
Idle> /vis/drawVolume
Idle> /vis/viewer/flush
```

In step 4, 3D scene data are sent from the remote host to the local host as DAWN-formatted data, and the local DAWN will visualize the data. The transferred data are saved as a file named `g4.prim` in the current directory of the local host.

Further information:

- http://geant4.kek.jp/GEANT4/vis/DAWN/About_DAWN.html
- http://geant4.kek.jp/GEANT4/vis/DAWN/G4PRIM_FORMAT_24/

Further information:

- Fukui Renderer DAWN:

  http://geant4.kek.jp/GEANT4/vis/DAWN/About_DAWN.html
- The DAWNFILE driver:

  http://geant4.kek.jp/GEANT4/vis/GEANT4/DAWNFILE_driver.html
- The DAWN-Network driver:

  http://geant4.kek.jp/GEANT4/vis/GEANT4/DAWNNET_driver.html
- Environmental variables to customize DAWN and DAWN drivers:

  http://geant4.kek.jp/GEANT4/vis/DAWN/DAWN_ENV.html

  http://geant4.kek.jp/GEANT4/vis/GEANT4/g4vis_on_linux.html
- DAWN format (g4.prim format) manual:

  http://geant4.kek.jp/GEANT4/vis/DAWN/G4PRIM_FORMAT_24/
- Geant4 Fukui University Group Home Page:

  http://geant4.kek.jp/GEANT4/vis/
- DAWNCUT:

  http://geant4.kek.jp/GEANT4/vis/DAWN/About_DAWNCUT.html
- DAVID:

  http://geant4.kek.jp/GEANT4/vis/DAWN/About_DAVID.html

- Geant4 Visualization Tutorial using the DAWN Renderer:

  http://geant4.slac.stanford.edu/Presentations/vis/GDAWNTutorial/G4DAWNTutorial.html

8.3.9. VRML

These drivers were developed by Satoshi Tanaka and Yasuhide Sawada (Fukui University). They generate VRML files, which describe 3D scenes to be visualized with a proper VRML viewer, at either a local or a remote host. It realizes virtual-reality visualization with your WWW browser. There are many excellent VRML viewers, which enable one to perform interactive spinning of detectors, walking and/or flying inside detectors or particle showers, interactive investigation of detailed detector geometry etc.

There are two kinds of VRML drivers: the VRMLFILE driver, and the VRML-Network driver. The VRMLFILE driver is usually recommended, since it is faster and safer in the sense that it is not affected by network conditions.

The VRMLFILE driver sends 3D data to your VRML viewer, which is running on the same host machine as Geant4, via an intermediate file named `g4.wrl` created in the current directory. This file can be re-visualization afterwards. In visualization, the name of the VRML viewer should be specified by setting the environment variable `G4VRML_VIEWER` beforehand. For example,

```
% setenv G4VRML_VIEWER  "netscape"
```

Its default value is `NONE`, which means that no viewer is invoked and only the file `g4.wrl` is generated.

Remote Visualization with the VRML-Network Driver

Visualization in Geant4 is considered to be "remote" when it is performed on a machine other than the Geant4 host. Some of the visualization drivers support this feature.

Usually, the visualization host is your local host, while the Geant4 host is a remote host where you log in, for example, with the `telnet` command. This enables distributed processing of Geant4 visualization, avoiding the transfer of large amounts of visualization data to your terminal display via the network.

In order to perform remote visualization with the VRML-Network driver, the following must be installed on your local host beforehand:

1. a VRML viewer
2. the Java application `g4vrmlview`.

The Java application `g4vrmlview` is included as part of the Geant4 package and is located at:

```
source/visualization/VRML/g4vrmlview/
```

Installation instructions for `g4vrmlview` can be found in the `README` file there, or on the WWW page below.

The following steps realize remote Geant4 visualization displayed with your local VRML browser:

1. Invoke the `g4vrmlview` on your local host, giving a VRML viewer name as its argument:

   ```
   Local_Host> java g4vrmlview  VRML_viewer_name
   ```

   For example, if you want to use the Netscape browser as your VRML viewer, execute `g4vrmlview` as follows:

   ```
   Local_Host> java g4vrmlview  netscape
   ```

   Of course, the command path to the VRML viewer should be properly set.

2. Log in to the remote host where a Geant4 executable is placed.
3. Set an environment variable on the remote host as follows:

```
Remote_Host> setenv G4VRML_HOST_NAME local_host_name
```

   For example, if you are working on the local host named "arkoop.kek.jp", set this environment variable as follows:

```
Remote_Host> setenv G4VRML_HOST_NAME arkoop.kek.jp
```

   This tells a Geant4 process running on the remote host where Geant4 Visualization should be performed, i.e., where the visualized views should be displayed.
4. Invoke a Geant4 process and perform visualization with the VRML-Network driver. For example:

```
Idle> /vis/open VRML2
Idle> /vis/drawVolume
Idle> /vis/viewer/update
```

In step 4, 3D scene data are sent from the remote host to the local host as VRML-formatted data, and the VRML viewer specified in step 3 is invoked by the `g4vrmlview` process to visualize the VRML data. The transferred VRML data are saved as a file named `g4.wrl` in the current directory of the local host.

Further information:

- http://geant4.kek.jp/GEANT4/vis/GEANT4/VRML_net_driver.html

Further information (VRML drivers):

- http://geant4.kek.jp/GEANT4/vis/GEANT4/VRML_file_driver.html
- http://geant4.kek.jp/GEANT4/vis/GEANT4/VRML_net_driver.html

Sample VRML files:

- http://geant4.kek.jp/GEANT4/vis/GEANT4/VRML2_FIG/

Further information (VRML language and browsers):

- http://www.vrmlsite.com/

8.3.10. RayTracer

This driver was developed by Makoto Asai and Minamimoto (Hirosihma Instutute of Technology). It performs ray-tracing visualization using the tracking routines of Geant4. It is, therefore, available for every kinds of shapes/solids which Geant4 can handle. It is also utilized for debugging the user's geometry for the tracking routines of Geant4. It is well suited for photo-realistic high quality output for presentation, and for intuitive debugging of detector geometry. It produces a JPEG file. This driver is by default listed in the available visualization drivers of user's application.

Some pieces of geometries may fail to show up in other visualization drivers (due to algorithms those drivers use to compute visualizable shapes and polygons), but RayTracer can handle any geometry that the Geant4 navigator can handle.

Because RayTracer in essence takes over Geant4's tracking routines for its own use, RayTracer cannot be used to visualize Trajectories or hits.

An X-Window version, called RayTracerX, can be selected by setting `G4VIS_BUILD_RATRACERX_DRIVER` at Geant4 library build time and `G4VIS_USE_RAYTRACERX` at application (user code) build time (assuming

you use the standard visualization manager, `G4VisExecutive`, or an equally smart vis manager). RayTracerX builds the same jpeg file as RayTracer, but simultaneously renders to screen so you can watch as rendering grows progressively smoother.

RayTracer has its own built-in commands - `/vis/rayTracer/`.... Alternatively, you can treat it as a normal vis system and use `/vis/viewer/`... commands, e.g:

```
/vis/open RayTracerX
/vis/drawVolume
/vis/viewer/set/viewpointThetaPhi 30 30
/vis/viewer/refresh
```

The view parameters are translated into the necessary RayTracer parameters.

RayTracer is compute intensive. If you are unsure of a good viewing angle or zoom factor, you might be advised to choose them with a faster renderer, such as OpenGL, and transfer the view parameters with `/vis/viewer/set/all`:

```
/vis/open OGLSXm  # or any of the OGL options.  Opens, say, viewer-0.
/vis/drawVolume
/vis/viewer/zoom  # plus any /vis/viewer/commands that get you the view you want.
/vis/open RayTracerX
/vis/viewer/set/all viewer-0
/vis/viewer/refresh
```

8.3.11. gMocren

The gMocrenFile driver creates a gdd file suitable for viewing with the gMocren volume visualizer. gMocren, a sophisticated tool for rendering volume data, can show volume data such as Geant4 dose distrubutions overlaid with scoring grids, trajectories and detector geometry. gMocren provides additional advanced functionality such as transfer functions, colormap editing, image rotation, image scaling, and image clipping.

gMocren is further described at http://geant4.kek.jp/gMocren/ . At this link you will find the gMocren download, the user manual, a tutorial and some example gdd data files.

Please note that the gMocren file driver is currently considered a Beta release. Users are encouraged to try this driver, and feedback is welcome, but users should be aware that features of this driver may change in upcoming releases.

To send volume data from Geant4 scoring to a gMocren file, the user needs to tell the gMocren driver the name of the specific scoring volume that is to be displayed. For scoring done in C++, this is the name of the sensitive volume. For command-based scoring, this is the name of the scoring mesh.

```
/vis/gMocren/setVolumeName <volume_name>
```

The following is an example of the minimum command sequence to send command-based scoring data to the a gMocren file:

```
# an example of a command-based scoring definition
/score/create/boxMesh scoringMesh       # name of the scoring mesh
/score/mesh/boxSize 10. 10. 10. cm      # dimension of the scoring mesh
/score/mesh/nBin 10 10 10               # number of divisions of the scoring mesh
/score/quantity/energyDeposit eDep      # quantity to be scored
/score/close
# configuration of the gMocren-file driver
/vis/scene/create
/vis/open gMocrenFile
/vis/gMocren/setVolumeName scoringMesh
```

To add detector geometry to this file:

```
/vis/viewer/flush
```

To add trajectories and primitive scorer hits to this file:

```
/vis/scene/add/trajectories
/vis/scene/add/pshits
/run/beamOn 1
```

gMocrenFile will write a file named G4_00.gd to the current directory. Subsequent draws will create files named g4_01.gdd, g4_02.gdd, etc. An alternate output directory can be specified with an environment variable:

```
export G4GMocrenFile_DEST_DIR=<someOtherDir/someOtherSubDir/>
```

View the resuling gMocren files with the gMocren viewer, available from: http://geant4.kek.jp/gMocren/ .

8.3.12. Visualization of detector geometry tree

ASCIITREE is a visualization driver that is not actually graphical but that dumps the volume hierarchy as a simple text tree.

Each call to /vis/viewer/flush or /vis/drawTree will dump the tree.

ASCIITree has command to control its verbosity, `/vis/ASCIITree/verbose`. The verbosity value controls the amount of information available, e.g., physical volume name alone, or also logical volume and solid names. If the volume is "sensitive" and/or has a "readout geometry", this may also be indicated. Also, the mass of the physical volume tree(s) can be printed (but beware - higher verbosity levels can be computationally intensive).

At verbosity level 4, ASCIITree calculates the mass of the complete geometry tree taking into account daughters up to the depth specified for each physical volume. The calculation involves subtracting the mass of that part of the mother that is occupied by each daughter and then adding the mass of the daughter, and so on down the hierarchy.

```
/vis/ASCIITree/Verbose 4
/vis/viewer/flush
"HadCalorimeterPhysical":0 / "HadCalorimeterLogical" / "HadCalorimeterBox"(G4Box),
                             1.8 m3 , 11.35 g/cm3
"HadCalColumnPhysical":-1 (10 replicas) / "HadCalColumnLogical" / "HadCalColumnBox"(G4Box),
                                          180000 cm3, 11.35 g/cm3
"HadCalCellPhysical":-1 (2 replicas) / "HadCalCellLogical" / "HadCalCellBox"(G4Box),
                                       90000 cm3, 11.35 g/cm3
"HadCalLayerPhysical":-1 (20 replicas) / "HadCalLayerLogical" / "HadCalLayerBox"(G4Box),
                                         4500 cm3, 11.35 g/cm3
"HadCalScintiPhysical":0 / "HadCalScintiLogical" / "HadCalScintiBox"(G4Box),
                           900 cm3, 1.032 g/cm3

Calculating mass(es)...
Overall volume of "worldPhysical":0, is 2400 m3
Mass of tree to unlimited depth is 22260.5 kg
```

Some more examples of ASCIITree in action:

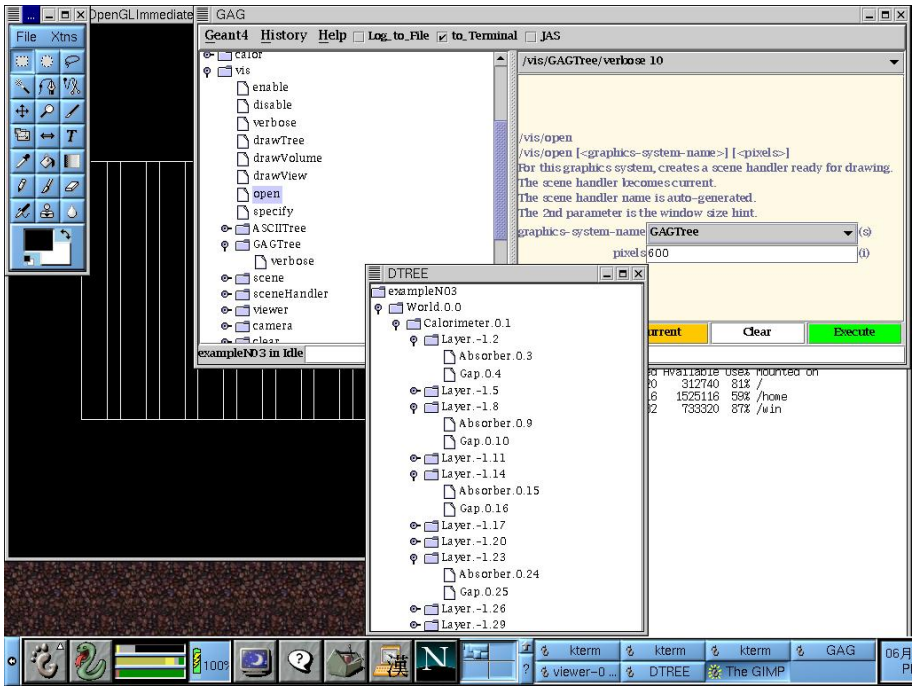
```
Idle> /vis/ASCIITree/verbose 1
Idle> /vis/drawTree
#  Set verbosity with "/vis/ASCIITree/verbose
#    <  10: - does not print daughters of repeated placements, does not repeat replicas.
#    >= 10: prints all physical volumes.
#  The level of detail is given by verbosity%10:
#  for each volume:
#    >=  0: physical volume name.
#    >=  1: logical volume name (and names of sensitive detector and readout geometry, if any).
#    >=  2: solid name and type.
#    >=  3: volume and density.
```

```
#    >=  5: daughter-subtracted volume and mass.
#  and in the summary at the end of printing:
#    >=  4: daughter-included mass of top physical volume(s) in scene to depth specified.
.....
"Calorimeter", copy no. 0, belongs to logical volume "Calorimeter"
  "Layer", copy no. -1, belongs to logical volume "Layer" (10 replicas)
    "Absorber", copy no. 0, belongs to logical volume "Absorber"
      "Gap", copy no. 0, belongs to logical volume "Gap"
.....
Idle> /vis/ASCIITree/verbose 15
Idle> /vis/drawTree
....
 "tube_phys":0 / "tube_L" / "tube"(G4Tubs), 395841 cm3, 1.782 mg/cm3,
                            9.6539e-08 mm3, 1.72032e-10 mg
   "divided_tube_phys":0 / "divided_tube_L" / "divided_tube"(G4Tubs), 65973.4 cm3,
                           1.782 mg/cm3, 7587.54 cm3, 13.521 g
     "divided_tube_inset_phys":0 / "divided_tube_inset_L" / "divided_tube_inset"(G4Tubs),
                                   58385.9 cm3, 1.782 mg/cm3, 6.03369e-09 mm3, 1.0752e-11 mg
       "sub_divided_tube_phys":0 / "sub_divided_tube_L" / "sub_divided_tube"(G4Tubs),
                                   14596.5 cm3, 1.782 mg/cm3, 12196.5 cm3, 21.7341 g
.....
Calculating mass(es)...
Overall volume of "expHall_P":0, is 8000 m3  and the daughter-included mass to unlimited depth
                                 is 78414 kg
.....
```

For the complete list of commands and options, see the Control...UICommands section of this user guide.

8.3.13. GAG Tree

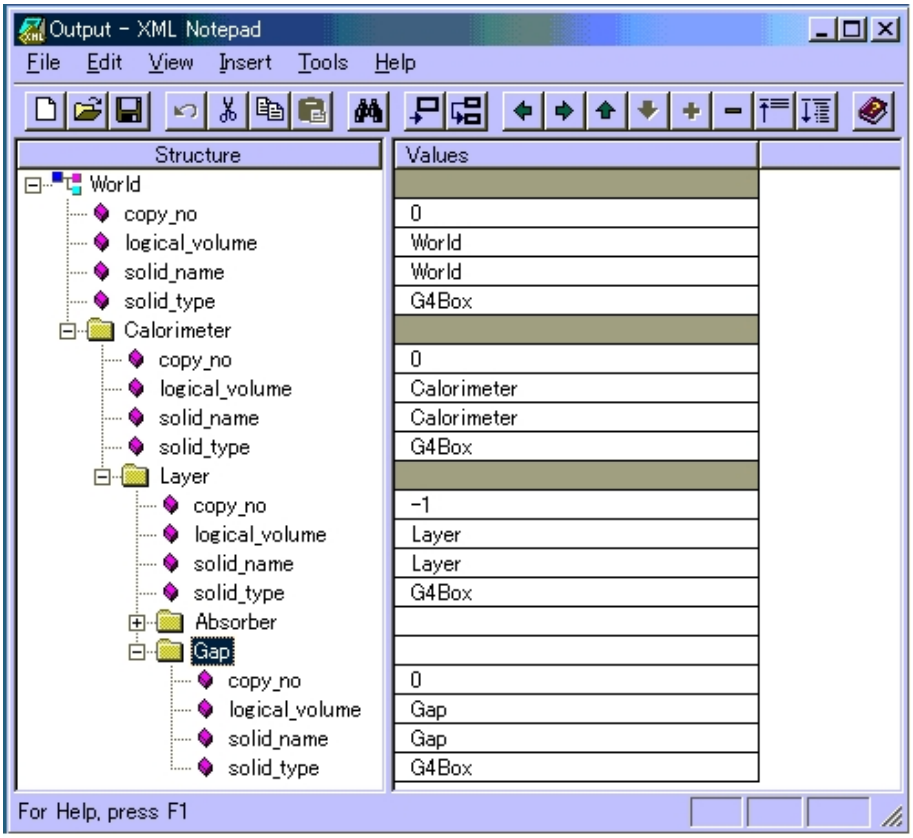
The GAGTree driver provides a listing of the detector geometry tree within GAG, the Geant Adaptive GUI, from $G4INSTALL/environments/MOMO/MOMO.jar. GAG allows "folding/un-folding" a part of the geometry tree, using the *Tree Widget* in Java:



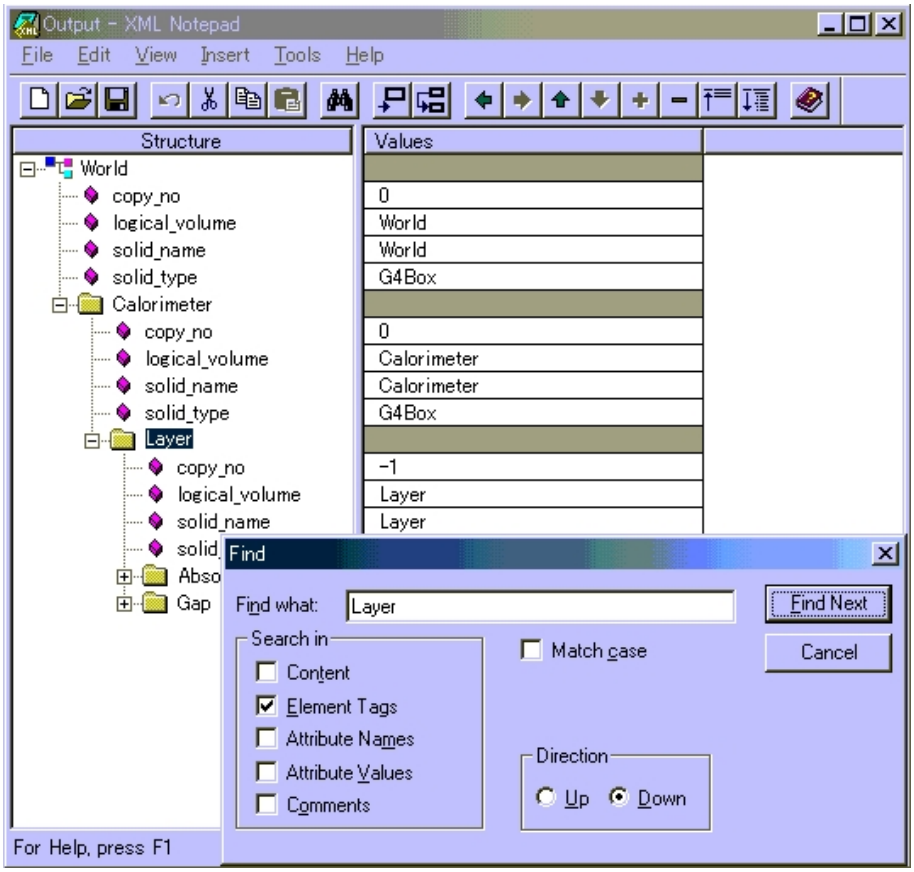
8.3.14. XML Tree

The XML description of the geometry tree can be created in Geant4 by the XML Tree driver. The XML source can also be edited on the fly. The created XML files are visualizable with any XML browser (in Windows, a good XML viewer is *XML Notepad*).

- Folding and un-folding:



- Searching a string:



8.4. Controlling Visualization from Commands

This section describes just a few of the more commonly used visualization commands. For the complete list of commands and options, see the Control...UICommands section of this user guide.

For simplicity, this section assumes that the Geant4 executable was compiled incorporating the DAWNFILE and the OpenGL-Xlib drivers. For details on creating an executable for visualization see Section 8.2.

8.4.1. Scene, scene handler, and viewer

In using the visualization commands, it is useful to know the concept of "scene", "scene handler", and "viewer". A "scene" is a set of visualizable raw 3D data. A "scene handler" is a graphics-data modeler, which processes raw data in a scene for later visualization. And a "viewer" generates images based on data processed by a scene handler. Roughly speaking, a set of a scene handler and a viewer corresponds to a visualization driver.

The steps of performing Geant4 visualization are explained below, though some of these steps may be done for you so that in practice you may use as few as just two commands (such as /vis/open OGLIX plus /vis/drawVolume) The seven steps of visualization are:

- Step 1. Create a scene handler and a viewer.
- Step 2. Create an empty scene.
- Step 3. Add raw 3D data to the created scene.
- Step 4. Attach the current scene handler to the current scene.
- Step 5. Set camera parameters, drawing style (wireframe/surface), etc.
- Step 6. Make the viewer execute visualization.
- Step 7. Declare the end of visualization for flushing.

These seven steps can be controlled explicitly to create multiple scenes and multiple viewers, each with its own set of parameters, with easy switching from one scene to another. But for the most common case of just having one scene and one viewer, many steps are handled implicitly for you.

8.4.2. Create a scene handler and a viewer: `/vis/open` command

Command "`/vis/open`" creates a scene handler and a viewer, which corresponds to Step 1.

Command: `/vis/open [driver_tag_name]`

- **Argument**

  A name of (a mode of) an available visualization driver.
- **Action**

  Create a visualization driver, i.e. a set of a scene hander and a viewer.
- **Example: Create the OpenGL-Xlib driver with its immediate mode**

  ```
  Idle> /vis/open OGLIX
  ```
- **Additional notes**

  For immediate viewers, such as OGLIX, your geometry will immediately be rendered in the new GL window

How to list available driver_tag_name:

```
Idle> help /vis/open
```

or

```
Idle> help /vis/sceneHandler/create
```

The list is, for example, displayed as follows:

```
.....
Candidates : DAWNFILE OGLIX OGLSX
.....
```

For additional options, see the Control...UICommands section of this user guide.

8.4.3. Create an empty scene: `/vis/scene/create` command

Command "`/vis/scene/create`" creates an empty scene, which corresponds to Step 2.

Command: `/vis/scene/create [scene_name]`

- **Argument**

  A name for this scene. Created for you if you don't specify one.

8.4.4. Visualization of a physical volume: `/vis/drawVolume` command

Command "`/vis/drawVolume`" adds a physical volume to the scene. It also does some of the other steps, if you haven't done them explicitly. It takes care of steps 2, 3, 4 and 6. Command "`/vis/viewer/flush`" should follow in order to do the final Step 7.

Commands:

```
/vis/drawVolume [physical-volume-name]
.....
Idle> /vis/viewer/flush
```

- **Argument**

  A physical-volume name. The default value is "world", which is omittable.
- **Action**

  Creates a scene consisting of the given physical volume and asks the current viewer to draw it. The scene becomes current. Command "`/vis/viewer/flush`" should follow this command in order to declare end of visualization.
- **Example: Visualization of the whole world with coordinate axes**

  ```
  Idle> /vis/drawVolume
  Idle> /vis/scene/add/axes 0 0 0 500 mm
  Idle> /vis/viewer/flush
  ```

8.4.5. Visualization of a logical volume: `/vis/specify` command

Command "`/vis/specify`" visualizes a logical volume. If allows you to control how much details is shown and whether to show booleans, voxels and readout geometries. It also does some of the other steps, if you haven't done them explicitly. It takes care of steps 2, 3, 4 and 6. Command "`/vis/viewer/flush`" should follow the command in order to do the final Step 7.

Command: `/vis/specify [logical-volume-name][depth-of-descent] [booleans-flag] [voxels-flag] [readout-flag]`

- **Argument**

  A logical-volume name.
- **Action**

  Creates a scene consisting of the given logical volume and asks the current viewer to draw it. The scene becomes current.
- **Example (visualization of a selected logical volume with coordinate axes)**

```
Idle> /vis/specify Absorber
Idle> /vis/scene/add/axes 0 0 0 500 mm
Idle> /vis/scene/add/text 0 0 0 mm 40 -100 -200 LogVol:Absorber
Idle> /vis/viewer/flush
```

For more options, see the Control...UICommands section of this user guide.

8.4.6. Visualization of trajectories: `/vis/scene/add/trajectories` command

Command "`/vis/scene/add/trajectories [smooth] [rich]`" adds trajectories to the current scene. The optional parameters "smooth" and/or "rich" (you may specify either, both or neither) invoke, if "smooth" is specified, the storing and displaying of extra points on curved trajectories and, if "rich" is specified, the storing, for possible subsequent selection and display, of additional information, such as volume names, creator process, energy deposited, global time. Be aware, of course, that this imposes computational and memory overheads. Note that this automatically issues the appropriate "`/tracking/storeTrajectory`" command so that trajectories are stored (by default they are not). The visualization is performed with the command "`/run/beamOn`" unless you have non-default values for /vis/scene/endOfEventAction or /vis/scene/endOfRunAction (described below).

Command: `/vis/scene/add/trajectories [smooth] [rich]`

- **Action**

  The command adds trajectories to the current scene. Trajectories are drawn at end of event when the scene in which they are added is current.
- **Example: Visualization of trajectories**

```
Idle> /vis/scene/add/trajectories
Idle> /run/beamOn 10
```

- **Additional note 1**

  See the section Section 8.7.3 Enhanced Trajectory Drawing for details on how to control how trajectories are color-coded.
- **Additional note 2**

  Events may be kept and reviewed at end of run with

```
Idle> /vis/reviewKeptEvents
```

  Keep all events with

```
Idle> /vis/scene/endOfEventAction accumulate [maxNumber]
```

  (see Section 8.4.11)

  or keep some chosen subset with

```
G4EventManager::GetEventManager()->KeepTheCurrentEvent();
```

as described in Example 6.4.

To suppress drawing during a run

```
Idle> /vis/disable
Idle> /run/beamOn 10000
```

then at end of run

```
Idle> /vis/enable
Idle> /vis/reviewKeptEvents
```

For more options, see the Control...UICommands section of this user guide.

8.4.7. Visualization of hits: `/vis/scene/add/hits` command

Command "`/vis/scene/add/hits`" adds hits to the current scene, assuming that you have a hit class and that the hits have visualization information. The visualization is performed with the command "`/run/beamOn`" unless you have non-default values for /vis/scene/endOfEventAction or /vis/scene/endOfRunAction (described above).

8.4.8. HepRep Attributes for Hits

The HepRep file formats, HepRepFile and HepRepXML, attach various attributes to hits such that you can view these attributes, label trajectories by these attributes or make visibility cuts based on these attributes. Examples of adding HepRep attributes to hit classes can be found in examples /extended/analysis/A01 and /extended/runAndEvent/RE01.

For example, in example RE01's class RE01CalorimeterHit.cc, available attributes will be:

- Hit Type
- Track ID
- Z Cell ID
- Phi Cell ID
- Energy Deposited
- Energy Deposited by Track
- Position
- Logical Volume

You can add additional attributes of your choosing by modifying the relevant part of the hit class (look for the methods GetAttDefs and CreateAttValues).

8.4.9. Basic camera workings: `/vis/viewer/` commands

Commands in the command directory "`/vis/viewer/`" set camera parameters and drawing style of the current viewer, which corresponds to Step 5. Note that the camera parameters and the drawing style should be set separately for each viewer. They can be initialized to the default values with command "`/vis/viewer/reset`". Some visualization systems, such as the VRML and HepRep browsers also allow camera control from the standalone graphics application.

Just a few of the camera commands are described here. For more commands, see the Control...UICommands section of this user guide.

Command: `/vis/viewer/set/viewpointThetaPhi [theta] [phi] [deg|rad]`

- **Arguments**

  Arguments "theta" and "phi" are polar and azimuthal camera angles, respectively. The default unit is "degree".
- **Action**

  Set a view point in direction of (theta, phi).
- **Example: Set the viewpoint in direction of (70 deg, 20 deg)** /

```
Idle> /vis/viewer/set/viewpointThetaPhi 70 20
```

- **Additional notes**

  Camera parameters should be set for each viewer. They are initialized with command "`/vis/viewer/reset`".

Command: `/vis/viewer/zoom [scale_factor]`

- **Argument**

  The scale factor. The command multiplies magnification of the view by this factor.
- **Action**

  Zoom up/down of view.
- **Example: Zoom up by factor 1.5**

```
Idle> /vis/viewer/zoom 1.5
```

- **Additional notes**

  Camera parameters should be set for each viewer. They are initialized with command "`/vis/viewer/reset`".

  A similar pair of commands, scale and scaleTo allow non-uniform scaling (i.e., zoom differently along different axes). For details, see the Control...UICommands section of this user guide.

Command: `/vis/viewer/set/style [style_name]`

- **Arguments**

  Candidate values of the argument are "wireframe" and "surface". ("w" and "s" also work.)
- **Action**

  Set a drawing style to wireframe or surface.
- **Example: Set the drawing style to "surface"**

```
Idle> /vis/viewer/set/style surface
```

- **Additional notes**

  The style of some geometry components may have been forced one way or the other through calls in compiled code. The set/style command will NOT override such force styles.

  Drawing style should be set for each viewer. The drawing style is initialized with command "`/vis/viewer/reset`".

8.4.10. Declare the end of visualization for flushing: `/vis/viewer/flush` command

Command: `/vis/viewer/flush`

- **Action**

  Declare the end of visualization for flushing.
- **Additional notes**

  Command "`/vis/viewer/flush`" should follow "`/vis/drawVolume`", "`/vis/specify`", etc in order to complete visualization. It corresponds to Step 7.

  The flush is done automatically after every /run/beamOn command unless you have non-default values for /vis/scene/endOfEventAction or /vis/scene/endOfRunAction (described above).

8.4.11. End of Event Action and End of Run Action: `/vis/viewer/endOfEventAction` and `/vis/viewer/endOfRunAction` commands

By default, a separate picture is created for each event. You can change this behavior to accumulate multiple events, or even multiple runs, in a single picture.

Command: `/vis/scene/endOfEventAction [refresh|accumulate]`

- **Action**

  Control how often the picture should be cleared. `refresh` means each event will be written to a new picture. `accumulate` means events will be accumulated into a single picture. Picture will be flushed at end of run, unless you have also set `/vis/scene/endOfRunAction accumulate`
- **Additional note**

  You may instead choose to use update commands from your BeginOfRunAction or EndOfEventAction, as in early examples, but now the vis manager ia able to do most of what most users require through the above commands.

Command: `/vis/scene/endOfRunAction [refresh|accumulate]`

- **Action**

  Control how often the picture should be cleared. `refresh` means each run will be written to a new picture. `accumulate` means runs will be accumulated into a single picture. To start a new picture, you must explicitly issue `/vis/viewer/refresh`, `/vis/viewer/update` or `/vis/viewer/flush`

8.4.12. HepRep Attributes for Trajectories

The HepRep file formats, HepRepFile and HepRepXML, attach various attributes to trajectories such that you can view these attributes, label trajectories by these attributes or make visibility cuts based on these attributes. If you use the default Geant4 trajectory class from /tracking/src/G4Trajectory.cc (this is what you get with the plain `/vis/scene/add/trajectories` command), available attributes will be:

- Track ID
- Parent ID
- Particle Name
- Charge
- PDG Encoding
- Momentum 3-Vector
- Momentum magnitude
- Number of points

Using `/vis/scene/add/trajectories rich` will get you additional attributes. You may also add additional attributes of your choosing by modifying the relevant part of G4Trajectory (look for the methods GetAttDefs and CreateAttValues). If you are using your own trajectory class, you may want to consider copying these methods from G4Trajectory.

8.4.13. How to save a visualized views to PostScript files

Most of the visualization drivers offer ways to save visualized views to PostScript files (or Encapsulated PostScript (EPS) files) by themselves.

- **DAWFILE**

  The DAWNFILE driver, which co-works with Fukui Renderer DAWN, generates "vectorized" PostScript data with "analytical hidden-line/surface removal", and so it is well suited for technical high-quality outputs for presentation, documentation, and debugging geometry. In the default setting of the DAWNFILE drivers, EPS files named "`g4_00.eps, g4_01.eps, g4_02.eps`,..." are automatically generated in the current directory each time when visualization is performed, and then a PostScript viewer "`gv`"is automatically invoked to visualize the generated EPS files.

  For large data sets, it may take time to generate the vectorized PostScript data. In such a case, visualize the 3D scene with a faster visualization driver beforehand for previewing, and then use the DAWNFILE drivers. For example, the following visualizes the whole detector with the OpenGL-Xlib driver (immediate mode) first, and then with the DAWNFILE driver to generate an EPS file `g4_XX.eps` to save the visualized view:

```
# Invoke the OpenGL visualization driver in its immediate mode
/vis/open OGLIX

# Camera setting
/vis/viewer/set/viewpointThetaPhi 20 20

# Camera setting
/vis/drawVolume
/vis/viewer/flush

# Invoke the DAWNFILE visualization driver
/vis/open DAWNFILE

# Camera setting
/vis/viewer/set/viewpointThetaPhi 20 20

# Camera setting
/vis/drawVolume
/vis/viewer/flush
```

  This is a good example to show that the visualization drivers are complementary to each other.
- **OpenInventor**

  In the OpenInventor drivers, you can simply click the "Print" button on their GUI to generate a PostScript file as a hard copy of a visualized view.
- **OpenGL**

  The OpenGL drivers can also generate PostScript files, either from a pull-down menu (Motif and Qt drivers) or with `/vis/ogl/printEPS`. It can generate either vector or bitmap PostScript data with `/vis/ogl/set/printMode` ("vectored" or "pixmap"). You can change the filename by `/vis/ogl/set/printMode` And the print size by `/vis/ogl/set/printSize` In generating vectorized PostScript data, hidden-surface removal is performed based on the painter's algorithm after dividing facets of shapes into small sub-triangles.

  Note that a fundamental limitation of the gl2ps library used for this PostScript printing causes the `/vis/viewer/set/hiddenMarker` command to be ignored. Trajectories will always be fully drawn in the printEPS output even when the hiddenMarker hidden line removal option has been set to hide these trajectories in the corresponding OpenGL view.

  The `/vis/ogl/set/printSize` command can be used to print EPS files even larger than the current screen resolution. This can allow creation of very large images, suitable for creation of posters, etc. The only size limitation is the graphics card's viewport dimension: GL_MAX_VIEWPORT_DIMS

```
# Invoke the OpenGL visualization driver in its stored mode
/vis/open OGLSX
```

```
# Camera setting
/vis/viewer/set/viewpointThetaPhi 20 20

# Camera setting
/vis/drawVolume
/vis/viewer/flush

# set print mode to vectored
/vis/ogl/set/printMode vectored

# set print size larger than screen
/vis/ogl/set/printSize 2000 2000

# print
/vis/ogl/printEPS
```

- **HepRep**

  The HepRApp HepRep Browser and WIRED4 JAS Plug-In can generate a wide variety of bitmap and vector output formats including PostScript and PDF.

8.4.14. Culling

"Culling" means to skip visualizing parts of a 3D scene. Culling is useful for avoiding complexity of visualized views, keeping transparent features of the 3D scene, and for quick visualization.

Geant4 Visualization supports the following 3 kinds of culling:

- Culling of invisible physical volumes
- Culling of low density physical volumes.
- Culling of covered physical volumes by others

In order that one or all types of the above culling are on, i.e., activated, the global culling flag should also be on.

Table 8.2 summarizes the default culling policies.

Culling Type	Default Value
global	ON
invisible	ON
low density	OFF
covered daughter	OFF

Table 8.2. The default culling policies.

The default threshold density of the low-density culling is 0.01 g/cm^3.

The default culling policies can be modified with the following visualization commands. (Below the argument `flag` takes a value of `true` or `false`.)

```
# global
/vis/viewer/set/culling  global  flag

# invisible
/vis/viewer/set/culling  invisible  flag

# low density
#   "value" is a proper value of a treshold density
#   "unit" is either g/cm3, mg/cm3 or kg/m3
/vis/viewer/set/culling  density  flag  value  unit

# covered daughter
/vis/viewer/set/culling  coveredDaughters  flag     density
```

The HepRepFile graphic system will, by default, include culled objects in the file so that they can still be made visible later from controls in the HepRep browser. If this behavior would cause files to be too large, you can instead

choose to have culled objects be omitted from the HepRep file. See details in the HepRepFile Driver section of this user guide.

8.4.15. Cut view

Sectioning

"Sectioning" means to make a thin slice of a 3D scene around a given plane. At present, this function is supported by the OpenGL drivers. The sectioning is realized by setting a sectioning plane before performing visualization. The sectioning plane can be set by the command,

```
/vis/viewer/set/sectionPlane on x y z units nx ny nz
```

where the vector (x,y,z) defines a point on the sectioning plane, and the vector (nx,ny,nz) defines the normal vector of the sectioning plane. For example, the following sets a sectioning plane to a yz plane at x = 2 cm:

```
Idle> /vis/viewer/set/sectionPlane  on  2.0  0.0  0.0  cm  1.0  0.0  0.0
```

Cutting away

"Cutting away" means to remove a half space, defined with a plane, from a 3D scene.

- Cutting away is supported by the DAWNFILE driver "off-line". Do the following:
  - Perform visualization with the DAWNFILE driver to generate a file `g4.prim`, describing the whole 3D scene.
  - Make the application "DAWNCUT" read the generated file to make a view of cutting away.

  See the following WWW page for details: http://geant4.kek.jp/GEANT4/vis/DAWN/About_DAWNCUT.html
- Alternatively, add up to three cutaway planes:

  ```
  /vis/viewer/addCutawayPlane 0 0 0 m 1 0 0
  /vis/viewer/addCutawayPlane 0 0 0 m 0 1 0
  ...
  ```

  and, for more that one plane, you can change the mode to
  - (a) "add" or, equivalently, "union" (default) or
  - (b) "multiply" or, equivalently, "intersection":

  ```
  /vis/viewer/set/cutawayMode multiply
  ```

  To de-activate:

  ```
  /vis/viewer/clearCutawayPlanes
  ```

  OpenGL supports this feature.

8.4.16. Tutorial macros

The followings are tutorial macros in the directory `examples/novice/N03/visTutor/`:

- exN03Vis0.mac:

  A basic macro for visualization of detector geometry and events using OpenGL in Immediate mode and DAWN.
- exN03Vis1.mac:

  A basic macro for visualization of detector geometry using OpenGL in Stored mode and DAWN.

- exN03Vis2.mac:

  A basic macro for visualization of detector geometry and events using OpenGL in Stored mode and DAWN.
- exN03Vis3.mac:

  A basic macro for demonstrating various drawing styles using OpenGL in Immediate mode and DAWN.
- exN03Vis4.mac:

  An example of visualizing specific logical volumes using OpenGL in Immediate mode and DAWN.
- exN03Vis5.mac:

  A basic macro for visualization of detector geometry and events using OpenInventor on Unix.
- exN03Vis6.mac:

  A basic macro for visualization of detector geometry and events using VRML.
- exN03Vis7.mac:

  A macro to demonstrate "batch" visualization to generate PostScript files with the DAWNFILE driver
- exN03Vis8.mac:

  A macro to demonstrate creation of a "multi-page" PostScript file with the DAWNFILE driver
- exN03Vis9.mac:

  A basic macro for visualization of detector geometry and events using OpenGL for Windows.
- exN03Vis10.mac:

  A basic macro for visualization of detector geometry and events using OpenInventor on Windows.
- exN03Vis11.mac:

  A basic macro for visualization of detector geometry and events using OpenGL in Stored Motif mode and DAWN.
- exN03Vis12.mac: and exN03Vis12.loop:

  A basic macro for demonstrating time slicing.
- exN03Vis13.mac: and exN03Vis3.loop:

  Time development of an electrmagnetic shower.
- exN03Vis14.mac:

  A basic macro for visualization of detector geometry and events using Qt in Stored mode.
- exN03Tree0.mac:

  A macro to demonstrate ASCII tree.
- exN03Tree1.mac:

  A macro to demonstrate GAG tree.

8.5. Controlling Visualization from Compiled Code

While a Geant4 simulation is running, visualization can be performed without user intervention. This is accomplished by calling methods of the Visualization Manager from methods of the user action classes (*G4UserRunAction* and *G4UserEventAction*, for example). In this section methods of the class *G4VVisManager*, which is part of the `graphics_reps` category, are described and examples of their use are given.

8.5.1. G4VVisManager

The Visualization Manager is implemented by classes *G4VisManager* and *G4VisExecutive*. See Section 8.2 "**Making a Visualization Executable**". In order that your Geant4 be compilable either with or without the visualization category, you should not use these classes directly in your C++ source code, other than in the `main()` function. Instead, you should use their abstract base class *G4VVisManager*, defined in the `intercoms` category.

The pointer to the concrete instance of the real Visualization Manager can be obtained as follows:

```
//----- Getting a pointer to the concrete Visualization Manager instance
G4VVisManager* pVVisManager = G4VVisManager::GetConcreteInstance();
```

The method `G4VVisManager::GetConcreteInstance()` returns `NULL` if Geant4 is not ready for visualization. Thus your C++ source code should be protected as follows:

```
//----- How to protect your C++ source codes in visualization
if (pVVisManager) {
    ....
    pVVisManager ->Draw (...);
    ....
}
```

8.5.2. Visualization of detector components

If you have already constructed detector components with logical volumes to which visualization attributes are properly assigned, you are almost ready for visualizing detector components. All you have to do is to describe proper visualization commands within your C++ codes, using the `ApplyCommand()` method.

For example, the following is sample C++ source codes to visualize the detector components:

```
//----- C++ source code: How to visualize detector components (2)
//                       ... using visualization commands in source codes

G4VVisManager* pVVisManager = G4VVisManager::GetConcreteInstance() ;

if(pVVisManager)
{
    ... (camera setting etc) ...
    G4UImanager::GetUIpointer()->ApplyCommand("/vis/drawVolume");
    G4UImanager::GetUIpointer()->ApplyCommand("/vis/viewer/flush");
}

//-----  end of C++ source code
```

In the above, you should also describe `/vis/open` command somewhere in your C++ codes or execute the command from (G)UI at the executing stage.

8.5.3. Visualization of trajectories

In order to visualize trajectories, you can use the method `void G4Trajectory::DrawTrajectory()` defined in the tracking category. In the implementation of this method, the following drawing method of *G4VVisManager* is used:

```
  //----- A drawing method of G4Polyline
  virtual void G4VVisManager::Draw (const G4Polyline&, ...) ;
```

The real implementation of this method is described in the class *G4VisManager*.

At the end of one event, a set of trajectories can be stored as a list of *G4Trajectory* objects. Therefore you can visualize trajectories, for example, at the end of each event, by implementing the method `MyEventAction::EndOfEventAction()` as follows:

```
//----- C++ source codes
void ExN03EventAction::EndOfEventAction(const G4Event* evt)
{
  .....
  // extract the trajectories and draw them
  if (G4VVisManager::GetConcreteInstance())
```

```
    {
     G4TrajectoryContainer* trajectoryContainer = evt->GetTrajectoryContainer();
     G4int n_trajectories = 0;
     if (trajectoryContainer) n_trajectories = trajectoryContainer->entries();

     for (G4int i=0; i < n_trajectories; i++)
        { G4Trajectory* trj=(G4Trajectory*)((*(evt->GetTrajectoryContainer()))[i]);
          if (drawFlag == "all") trj->DrawTrajectory(50);
          else if ((drawFlag == "charged")&&(trj->GetCharge() != 0.))
                                  trj->DrawTrajectory(50);
          else if ((drawFlag == "neutral")&&(trj->GetCharge() == 0.))
                                  trj->DrawTrajectory(50);
        }
  }
}
//----- end of C++ source codes
```

8.5.4. Enhanced trajectory drawing

It is possible to use the enhanced trajectory drawing functionality in compiled code as well as from commands. Multiple trajectory models can be instantiated, configured and registered with G4VisManager. For details, see the section on Section 8.7.4 Enhanced Trajectory Drawing.

8.5.5. HepRep Attributes for Trajectories

The HepRep file formats, HepRepFile and HepRepXML, attach various attributes to trajectories such that you can view these attributes, label trajectories by these attributes or make visibility cuts based on these attributes. If you use the default Geant4 trajectory class, from /tracking/src/G4Trajectory.cc, available attributes will be:

- Track ID
- Parent ID
- Particle Name
- Charge
- PDG Encoding
- Momentum 3-Vector
- Momentum magnitude
- Number of points

You can add additional attributes of your choosing by modifying the relevant part of G4Trajectory (look for the methods GetAttDefs and CreateAttValues). If you are using your own trajectory class, you may want to consider copying these methods from G4Trajectory.

8.5.6. Visualization of hits

Hits are visualized with classes *G4Square* or *G4Circle*, or other user-defined classes inheriting the abstract base class *G4VMarker*. Drawing methods for hits are not supported by default. Instead, ways of their implementation are guided by virtual methods, `G4VHit::Draw()` and `G4VHitsCollection::DrawAllHits()`, of the abstract base classes *G4VHit* and *G4VHitsCollection*. These methods are defined as empty functions in the `digits+hits` category. You can overload these methods, using the following drawing methods of class *G4VVisManager*, in order to visualize hits:

```
//----- Drawing methods of G4Square and G4Circle
virtual void G4VVisManager::Draw (const G4Circle&, ...) ;
virtual void G4VVisManager::Draw (const G4Square&, ...) ;
```

The real implementations of these `Draw()` methods are described in class *G4VisManager*.

The overloaded implementation of `G4VHits::Draw()` will be held by, for example, class *MyTrackerHits* inheriting *G4VHit* as follows:

```
//----- C++ source codes: An example of giving concrete implementation of
```

```
 //       G4VHit::Draw(), using  class MyTrackerHit : public G4VHit {...}
 //
void MyTrackerHit::Draw()
{
   G4VVisManager* pVVisManager = G4VVisManager::GetConcreteInstance();
   if(pVVisManager)
   {
     // define a circle in a 3D space
     G4Circle circle(pos);
     circle.SetScreenSize(0.3);
     circle.SetFillStyle(G4Circle::filled);

     // make the circle red
     G4Colour colour(1.,0.,0.);
     G4VisAttributes attribs(colour);
     circle.SetVisAttributes(attribs);

     // make a 3D data for visualization
     pVVisManager->Draw(circle);
   }
 }

 //----- end of C++ source codes
```

The overloaded implementation of `G4VHitsCollection::DrawAllHits()` will be held by, for example, class *MyTrackerHitsCollection* inheriting class *G4VHitsCollection* as follows:

```
 //----- C++ source codes: An example of giving concrete implementation of
 //       G4VHitsCollection::Draw(),
 //       using  class MyTrackerHit : public G4VHitsCollection{...}
 //
 void MyTrackerHitsCollection::DrawAllHits()
 {
   G4int n_hit = theCollection.entries();
   for(G4int i=0;i < n_hit;i++)
   {
     theCollection[i].Draw();
   }
 }

 //----- end of C++ source codes
```

Thus, you can visualize hits as well as trajectories, for example, at the end of each event by implementing the method `MyEventAction::EndOfEventAction()` as follows:

```
 void MyEventAction::EndOfEventAction()
 {
   const G4Event* evt = fpEventManager->GetConstCurrentEvent();

   G4SDManager * SDman = G4SDManager::GetSDMpointer();
   G4String colNam;
   G4int trackerCollID = SDman->GetCollectionID(colNam="TrackerCollection");
   G4int calorimeterCollID = SDman->GetCollectionID(colNam="CalCollection");

   G4TrajectoryContainer * trajectoryContainer = evt->GetTrajectoryContainer();
   G4int n_trajectories = 0;
   if(trajectoryContainer)
   { n_trajectories = trajectoryContainer->entries(); }

   G4HCofThisEvent * HCE = evt->GetHCofThisEvent();
   G4int n_hitCollection = 0;
   if(HCE)
   { n_hitCollection = HCE->GetCapacity(); }

   G4VVisManager* pVVisManager = G4VVisManager::GetConcreteInstance();

   if(pVVisManager)
   {

     // Declare begininng of visualization
     G4UImanager::GetUIpointer()->ApplyCommand("/vis/scene/notifyHandlers");
```

```
    // Draw trajectories
    for(G4int i=0; i < n_trajectories; i++)
    {
        (*(evt->GetTrajectoryContainer()))[i]->DrawTrajectory();
    }

    // Construct 3D data for hits
    MyTrackerHitsCollection* THC
      = (MyTrackerHitsCollection*)(HCE->GetHC(trackerCollID));
    if(THC) THC->DrawAllHits();
    MyCalorimeterHitsCollection* CHC
      = (MyCalorimeterHitsCollection*)(HCE->GetHC(calorimeterCollID));
    if(CHC) CHC->DrawAllHits();

    // Declare end of visualization
    G4UImanager::GetUIpointer()->ApplyCommand("/vis/viewer/update");

  }

}

//----- end of C++ codes
```

You can re-visualize a physical volume, where a hit is detected, with a highlight color, in addition to the whole set of detector components. It is done by calling a drawing method of a physical volume directly. The method is:

```
//----- Drawing methods of a physical volume
virtual void Draw (const G4VPhysicalVolume&, ...) ;
```

This method is, for example, called in a method `MyXXXHit::Draw()`, describing the visualization of hits with markers. The following is an example for this:

```
//----- C++ source codes: An example of visualizing hits with
void MyCalorimeterHit::Draw()
{
  G4VVisManager* pVVisManager = G4VVisManager::GetConcreteInstance();
  if(pVVisManager)
  {
    G4Transform3D trans(rot,pos);
    G4VisAttributes attribs;
    G4LogicalVolume* logVol = pPhys->GetLogicalVolume();
    const G4VisAttributes* pVA = logVol->GetVisAttributes();
    if(pVA) attribs = *pVA;
    G4Colour colour(1.,0.,0.);
    attribs.SetColour(colour);
    attribs.SetForceSolid(true);

    //----- Re-visualization of a selected physical volume with red color
    pVVisManager->Draw(*pPhys,attribs,trans);

  }
}

//----- end of C++ codes
```

8.5.7. HepRep Attributes for Hits

The HepRep file formats, HepRepFile and HepRepXML, attach various attributes to hits such that you can view these attributes, label trajectories by these attributes or make visibility cuts based on these attributes. Examples of adding HepRep attributes to hit classes can be found in examples /extended/analysis/A01 and /extended/runAndEvent/RE01.

For example, in example RE01's class RE01CalorimeterHit.cc, available attributes will be:

- Hit Type

- Track ID
- Z Cell ID
- Phi Cell ID
- Energy Deposited
- Energy Deposited by Track
- Position
- Logical Volume

You can add additional attributes of your choosing by modifying the relevant part of the hit class (look for the methods GetAttDefs and CreateAttValues).

8.5.8. Visualization of text

In Geant4 Visualization, a text, i.e., a character string, is described by class *G4Text* inheriting *G4VMarker* as well as *G4Square* and *G4Circle*. Therefore, the way to visualize text is the same as for hits. The corresponding drawing method of *G4VVisManager* is:

```
//----- Drawing methods of G4Text
virtual void G4VVisManager::Draw (const G4Text&, ...);
```

The real implementation of this method is described in class *G4VisManager*.

8.5.9. Visualization of polylines and tracking steps

Polylines, i.e., sets of successive line segments, are described by class *G4Polyline*. For *G4Polyline*, the following drawing method of class *G4VVisManager* is prepared:

```
 //----- A drawing method of G4Polyline
  virtual void G4VVisManager::Draw (const G4Polyline&, ...) ;
```

The real implementation of this method is described in class *G4VisManager*.

Using this method, C++ source codes to visualize *G4Polyline* are described as follows:

```
//----- C++ source code: How to visualize a polyline
 G4VVisManager* pVVisManager = G4VVisManager::GetConcreteInstance();

 if (pVVisManager) {
     G4Polyline polyline ;

     ..... (C++ source codes to set vertex positions, color, etc)

     pVVisManager -> Draw(polyline);

 }

 //----- end of C++ source codes
```

Tracking steps are able to be visualized based on the above visualization of *G4Polyline*. You can visualize tracking steps at each step automatically by writing a proper implementation of class *MySteppingAction* inheriting *G4UserSteppingAction*, and also with the help of the Run Manager.

First, you must implement a method, `MySteppingAction::UserSteppingAction()`. A typical implementation of this method is as follows:

```
 //----- C++ source code: An example of visualizing tracking steps
 void MySteppingAction::UserSteppingAction()
```

```
  {
      G4VVisManager* pVVisManager = G4VVisManager::GetConcreteInstance();

      if (pVVisManager) {

        //----- Get the Stepping Manager
        const G4SteppingManager* pSM = GetSteppingManager();

        //----- Define a line segment
        G4Polyline polyline;
        G4double charge = pSM->GetTrack()->GetDefinition()->GetPDGCharge();
        G4Colour colour;
        if      (charge < 0.) colour = G4Colour(1., 0., 0.);
        else if (charge < 0.) colour = G4Colour(0., 0., 1.);
        else                  colour = G4Colour(0., 1., 0.);
        G4VisAttributes attribs(colour);
        polyline.SetVisAttributes(attribs);
        polyline.push_back(pSM->GetStep()->GetPreStepPoint()->GetPosition());
        polyline.push_back(pSM->GetStep()->GetPostStepPoint()->GetPosition());

        //----- Call a drawing method for G4Polyline
        pVVisManager -> Draw(polyline);

      }
  }

  //----- end of C++ source code
```

Next, in order that the above C++ source code works, you have to pass the information of the *MySteppingAction* to the Run Manager in the `main()` function:

```


  //----- C++ source code: Passing what to do at each step to the Run Manager

  int main()
  {
     ...

     // Run Manager
     G4RunManager * runManager = new G4RunManager;

     // User initialization classes
     ...
     runManager->SetUserAction(new MySteppingAction);
     ...
  }

  //----- end of C++ source code
```

Thus you can visualize tracking steps with various visualization attributes, e.g., color, at each step, automatically.

As well as tracking steps, you can visualize any kind 3D object made of line segments, using class *G4Polyline* and its drawing method, defined in class *G4VVisManager*. See, for example, the implementation of the `/vis/scene/add/axes` command.

8.5.10. Visualization User Action

You can implement the `Draw` method of `G4VUserVisAction`, e.g., the class definition could be:

```
class StandaloneVisAction: public G4VUserVisAction {
  void Draw();
};
```

and the implementation:

```
void StandaloneVisAction::Draw() {
```

```
  G4VVisManager* pVisManager = G4VVisManager::GetConcreteInstance();
  if (pVisManager) {

    // Simple box...
    pVisManager->Draw(G4Box("box",2*m,2*m,2*m),
                      G4VisAttributes(G4Colour(1,1,0)));

    // Boolean solid...
    G4Box boxA("boxA",3*m,3*m,3*m);
    G4Box boxB("boxB",1*m,1*m,1*m);
    G4SubtractionSolid subtracted("subtracted_boxes",&boxA,&boxB,
                       G4Translate3D(3*m,3*m,3*m));
    pVisManager->Draw(subtracted,
                      G4VisAttributes(G4Colour(0,1,1)),
                      G4Translate3D(6*m,6*m,6*m));
  }
}
```

Explicit use of polyhedron objects is equivalent, e.g.:

```


    // Same, but explicit polyhedron...
    G4Polyhedron* pA = G4Box("boxA",3*m,3*m,3*m).CreatePolyhedron();
    G4Polyhedron* pB = G4Box("boxB",1*m,1*m,1*m).CreatePolyhedron();
    pB->Transform(G4Translate3D(3*m,3*m,3*m));
    G4Polyhedron* pSubtracted = new G4Polyhedron(pA->subtract(*pB));
    G4VisAttributes subVisAtts(G4Colour(0,1,1));
    pSubtracted->SetVisAttributes(&subVisAtts);
    pVisManager->Draw(*pSubtracted,G4Translate3D(6*m,6*m,6*m));
    delete pA;
    delete pB;
    delete pSubtracted;
```

If efficiency is an issue, create the objects in the constructor, delete them in the destructor and draw them in your `Draw` method. Anyway, an instance of your class needs to be registered with the vis manager, e.g.:

```
  ...
  G4VisManager* visManager = new G4VisExecutive;
  visManager->Initialize ();

  visManager->SetUserAction
    (new StandaloneVisAction,
     G4VisExtent(-5*m,5*m,-5*m,5*m,-5*m,5*m));  // 2nd argument optional.
  ...
```

then activate by adding to a scene, e.g:

```
/control/verbose 2
/vis/verbose c
/vis/open OGLSXm
/vis/scene/create
#/vis/scene/add/userAction
/vis/scene/add/userAction -10 10 -10 10 -10 10 m
#/vis/scene/add/axes 0 0 0 10 m
#/vis/scene/add/scale 10 m
/vis/sceneHandler/attach
/vis/viewer/refresh
```

The extent can be added on registration or on the command line or neither (if the extent of the scene is set by other components). Your `Draw` method will be called whenever needed to refresh the screen or rebuild a graphics database, for any chosen viewer. The scene can be attached to any scene handler and your drawing will be shown.

8.5.11. Standalone Visualization

The above raises the possibility of using Geant4 as a "standalone" graphics package without invoking the run manager. The following main program, together with a user visualization action and a macro file, will allow you to view your drawing interactively on any of the supported graphics systems.

```
#include "globals.hh"
#include "G4VisExecutive.hh"
#include "G4VisExtent.hh"
#include "G4UImanager.hh"
#include "G4UIterminal.hh"
#include "G4UItcsh.hh"

#include "StandaloneVisAction.hh"

int main() {

  G4VisManager* visManager = new G4VisExecutive;
  visManager->Initialize ();

  visManager->SetUserAction
    (new StandaloneVisAction,
     G4VisExtent(-5*m,5*m,-5*m,5*m,-5*m,5*m));  // 2nd argument optional.

  G4UImanager* UI = G4UImanager::GetUIpointer ();
  UI->ApplyCommand ("/control/execute standalone.g4m");

  G4UIsession* session = new G4UIterminal(new G4UItcsh);
  session->SessionStart();

  delete session;
  delete visManager;
}
```

8.6. Visualization Attributes

Visualization attributes are extra pieces of information associated with the visualizable objects. This information is necessary only for visualization, and is not included in geometrical information such as shapes, position, and orientation. Typical examples of visualization attributes are Color, Visible/Invisible, Wireframe/Solid. For example, in visualizing a box, the Visualization Manager must know its colour. If an object to be visualized has not been assigned a set of visualization attributes, then an appropriate default set is used automatically.

A set of visualization attributes is held by an instance of class *G4VisAttributes* defined in the `graphics_reps` category. In the following, we explain the main fields of the *G4VisAttributes* one by one.

8.6.1. Visibility

Visibility is a boolean flag to control the visibility of objects that are passed to the Visualization Manager for visualization. Visibility is set with the following access function:

```
    void G4VisAttributes::SetVisibility (G4bool visibility);
```

If you give `false` to the argument, and if culling is activated (see below), visualization is skipped for objects for which this set of visualization attributes is assigned. The default value of visibility is `true`.

Note that whether an object is visible or not is also affected by the current culling policy, which can be tuned with visualization commands.

By default the following public static function is defined:

```
    static const G4VisAttributes& GetInvisible();
```

which returns a reference to a const object in which visibility is set to `false`. It can be used as follows:

```
    experimentalHall_logical -> SetVisAttributes (G4VisAttributes::GetInvisible());
```

Direct access to the public static const data member `G4VisAttributes::Invisible` is also possible but deprecated on account of initialisation issues with dynamic libraries.

8.6.2. Colour

8.6.2.1. Construction

Class *G4Colour* (an equivalent class name, *G4Color*, is also available) has 4 fields, which represent the RGBA (red, green, blue, and alpha) components of colour. Each component takes a value between 0 and 1. If an irrelevant value, i.e., a value less than 0 or greater than 1, is given as an argument of the constructor, such a value is automatically clipped to 0 or 1. Alpha is opacity, which is not used at present. You can use its default value `1`, which means "opaque" in instantiation of *G4Colour*.

A *G4Colour* object is instantiated by giving red, green, and blue components to its constructor, i.e.,

```
G4Colour::G4Colour ( G4double r = 1.0,
                     G4double g = 1.0,
                     G4double b = 1.0,
                     G4double a = 1.0);
                             // 0<=red, green, blue <= 1.0
```

The default value of each component is 1.0. That is to say, the default colour is "white" (opaque).

For example, colours which are often used can be instantiated as follows:

```
G4Colour  white   ()             ;  // white
G4Colour  white   (1.0, 1.0, 1.0) ;  // white
G4Colour  gray    (0.5, 0.5, 0.5) ;  // gray
G4Colour  black   (0.0, 0.0, 0.0) ;  // black
G4Colour  red     (1.0, 0.0, 0.0) ;  // red
G4Colour  green   (0.0, 1.0, 0.0) ;  // green
G4Colour  blue    (0.0, 0.0, 1.0) ;  // blue
G4Colour  cyan    (0.0, 1.0, 1.0) ;  // cyan
G4Colour  magenta (1.0, 0.0, 1.0) ;  // magenta
G4Colour  yellow  (1.0, 1.0, 0.0) ;  // yellow
```

It is also possible to instantiate common colours through static public data member functions:

```
static const G4Colour& White   ();
static const G4Colour& Gray    ();
static const G4Colour& Grey    ();
static const G4Colour& Black   ();
static const G4Colour& Red     ();
static const G4Colour& Green   ();
static const G4Colour& Blue    ();
static const G4Colour& Cyan    ();
static const G4Colour& Magenta ();
static const G4Colour& Yellow  ();
```

For example, a local *G4Colour* could be constructed as:

```
G4Colour myRed(G4Colour::Red());
```

After instantiation of a *G4Colour* object, you can access to its components with the following access functions:

```
G4double G4Colour::GetRed   () const ; // Get the red   component.
G4double G4Colour::GetGreen () const ; // Get the green component.
G4double G4Colour::GetBlue  () const ; // Get the blue  component.
```

8.6.2.2. Colour Map

G4Colour also provides a static colour map, giving access to predefined *G4Colour*'s through a *G4String* key. The default mapping is:

```
G4String           G4Colour
---------------------------------------
white              G4Colour::White   ()
gray               G4Colour::Gray    ()
grey               G4Colour::Grey    ()
black              G4Colour::Black   ()
red                G4Colour::Red     ()
green              G4Colour::Green   ()
blue               G4Colour::Blue    ()
cyan               G4Colour::Cyan    ()
magenta            G4Colour::Magenta ()
yellow             G4Colour::Yellow  ()
```

Colours can be retrieved through the GetColour method:

```
bool G4Colour::GetColour(const G4String& key, G4Colour& result)
```

For example:

```
G4Colour myColour(G4Colour::Black());
if (G4Colour::GetColour("red", myColour)) {
  // Successfully retrieved colour "red". myColour is now red
}
else {
  // Colour did not exist in map. myColour is still black
}
```

If the key is not registered in the colour map, a warning message is printed and the input colour is not changed. The colour map is case insensitive.

It is also possible to load user defined *G4Colour*'s into the map through the public AddToMap method. For example:

```
G4Colour myColour(0.2, 0.2, 0.2, 1);
G4Colour::AddToMap("custom", myColour);
```

This loads a user defined *G4Colour* with key "custom" into the colour map.

8.6.2.3. Colour and G4VisAttributes

Class *G4VisAttributes* holds its colour entry as an object of class *G4Colour*. A *G4Colour* object is passed to a *G4VisAttributes* object with the following access functions:

```
//----- Set functions of G4VisAttributes.
void G4VisAttributes::SetColour (const G4Colour& colour);
void G4VisAttributes::SetColor (const G4Color& color );
```

We can also set RGBA components directly:

```
//----- Set functions of G4VisAttributes
void G4VisAttributes::SetColour ( G4double red   ,
                                  G4double green ,
                                  G4double blue  ,
                                  G4double alpha = 1.0);

void G4VisAttributes::SetColor  ( G4double red   ,
                                  G4double green ,
                                  G4double blue  ,
                                  G4double alpha = 1.);
```

The following constructor with *G4Colour* as its argument is also supported:

```
//----- Constructor of G4VisAttributes
```

```
    G4VisAttributes::G4VisAttributes (const G4Colour& colour);
```

Note that colour assigned to a *G4VisAttributes* object is not always the colour that ultimately appears in the visualization. The ultimate appearance may be affected by shading and lighting models applied in the selected visualization driver or stand-alone graphics system.

8.6.3. Forcing attributes

As you will see later, you can select a "drawing style" from various options. For example, you can select your detector components to be visualized in "wireframe" or with "surfaces". In the former, only the edges of your detector are drawn and so the detector looks transparent. In the latter, your detector looks opaque with shading effects.

The forced wireframe and forced solid styles make it possible to mix the wireframe and surface visualization (if your selected graphics system supports such visualization). For example, you can make only the outer wall of your detector "wired" (transparent) and can see inside in detail.

Forced wireframe style is set with the following access function:

```
    void G4VisAttributes::SetForceWireframe (G4bool force);
```

If you give `true` as the argument, objects for which this set of visualization attributes is assigned are always visualized in wireframe even if in general, the surface drawing style has been requested. The default value of the forced wireframe style is `false`.

Similarly, forced solid style, i.e., to force that objects are always visualized with surfaces, is set with:

```
    void G4VisAttributes::SetForceSolid (G4bool force);
```

The default value of the forced solid style is `false`, too.

You can also force auxiliary edges to be visible. Normally they are not visible unless you set the appropriate view parameter. Forcing the auxiliary edges to be visible means that auxiliary edges will be seen whatever the view parameters.

Auxiliary edges are not genuine edges of the volume. They may be in a curved surface made out of polygons, for example, or in plane surface of complicated shape that has to be broken down into simpler polygons. HepPolyhedron breaks all surfaces into triangles or quadrilaterals. There will be auxiliary edges for any volumes with a curved surface, such as a tube or a sphere, or a volume resulting from a Boolean operation. Normally, they are not shown, but sometimes it is useful to see them. In particular, a sphere, because it has no egdes, will not be seen in wireframe mode in some graphics systems unless requested by the view parameters or forced, as described here.

To force auxiliary edges to be visible, use:

```
    void G4VisAttributes::SetForceAuxEdgeVisible (G4bool force);
```

The default value of the force auxiliary edges visible flag is `false`.

For volumes with edges that are parts of a circle, such as a tube (G4Tubs), etc., it is possible to force the precision of polyhedral representation for visualisation. This is recommended for volumes containing only a small angle of circle, for example, a thin tube segment.

For visualisation, a circle is represented by an N-sided polygon. The default is 24 sides or segments. The user may change this for all volumes in a particular viewer at run time with /vis/viewer/set/lineSegmentsPerCircle; alternatively it can be forced for a particular volume with:

```
    void G4VisAttributes::SetForceLineSegmentsPerCircle (G4int nSegments);
```

8.6.4. Constructors of G4VisAttributes

The following constructors are supported for class *G4VisAttributes*:

```
//----- Constructors of class G4VisAttributes
G4VisAttributes (void);
G4VisAttributes (G4bool visibility);
G4VisAttributes (const G4Colour& colour);
G4VisAttributes (G4bool visibility, const G4Colour& colour);
```

8.6.5. How to assign G4VisAttributes to a logical volume

In constructing your detector components, you may assign a set of visualization attributes to each "logical volume" in order to visualize them later (if you do not do this, the graphics system will use a default set). You cannot make a solid such as *G4Box* hold a set of visualization attributes; this is because a solid should hold only geometrical information. At present, you cannot make a physical volume hold one, but there are plans to design a memory-efficient way to do it; however, you can visualize a transient piece of solid or physical volume with a temporary assigned set of visualization attributes.

Class *G4LogicalVolume* holds a pointer of *G4VisAttributes.* This field is set and referenced with the following access functions:

```
//----- Set functions of G4VisAttributes
void G4VisAttributes::SetVisAttributes (const G4VisAttributes* pVA);
void G4VisAttributes::SetVisAttributes (const G4VisAttributes& VA);

//----- Get functions of G4VisAttributes
const G4VisAttributes* G4VisAttributes::GetVisAttributes () const;
```

The following is sample C++ source codes for assigning a set of visualization attributes with cyan colour and forced wireframe style to a logical volume:

```
//----- C++ source codes: Assigning G4VisAttributes to a logical volume
...
     // Instantiation of a logical volume
myTargetLog = new G4LogicalVolume( myTargetTube,BGO, "TLog", 0, 0, 0);
...
     // Instantiation of a set of visualization attributes with cyan colour
G4VisAttributes * calTubeVisAtt = new G4VisAttributes(G4Colour(0.,1.,1.));
     // Set the forced wireframe style
calTubeVisAtt->SetForceWireframe(true);
     // Assignment of the visualization attributes to the logical volume
myTargetLog->SetVisAttributes(calTubeVisAtt);

//----- end of C++ source codes
```

Note that the life of the visualization attributes must be at least as long as the objects to which they are assigned; it is the users' responsibility to ensure this, and to delete the visualization attributes when they are no longer needed (or just leave them to die at the end of the job).

8.6.6. Additional User-Defined Attributes

Geant4 Trajectories and Hits can be assigned additional arbitrary attributes that will be displayed when you click on the relevant object in the WIRED or FRED HepRep browsers. WIRED then lets you label objects by any of these attributes or cut visibility based on these attributes.

Define the attributes with lines such as:

```
std::map<G4String,G4AttDef>* store = G4AttDefStore::GetInstance("G4Trajectory",isNew);
G4String PN("PN");
(*store)[PN] = G4AttDef(PN,"Particle Name","Physics","","G4String");
G4String IMom("IMom");
(*store)[IMom] = G4AttDef(IMom, "Momentum of track at start of trajectory", "Physics", "",
```

```
                                        "G4ThreeVector");
```

Then fill the attributes with lines such as:

```
    std::vector<G4AttValue>* values = new std::vector<G4AttValue>;
    values->push_back(G4AttValue("PN",ParticleName,""));
    s.seekp(std::ios::beg);
    s << G4BestUnit(initialMomentum,"Energy") << std::ends;
    values->push_back(G4AttValue("IMom",c,""));
```

See geant4/source/tracking/src/G4Trajectory.cc for a good example.

G4AttValue objects are light, containing just the value; for the long description and other sharable information the *G4AttValue* object refers to a *G4AttDef* object. They are based on the HepRep standard described at http://www.slac.stanford.edu/~perl/heprep/ . Geant4 also provides an *G4AttDefStore*.

Geant4 provides some default examples of the use of this facility in the trajectory classes in /source/tracking such as *G4Trajectory*, *G4SmoothTrajectory*. *G4Trajectory::CreateAttValues* shows how *G4AttValue* objects can be made and *G4Trajectory::GetAttDefs* shows how to make the corresponding *G4AttDef* objects and use the *G4AttDefStore*. Note that the "user" of CreateAttValues guarantees to destroy them; this is a way of allowing creation on demand and leaving the *G4Trajectory* object, for example, free of such objects in memory. The comments in *G4VTrajectory.hh* explain further and additional insights might be obtained by looking at two methods which use them, namely *G4VTrajectory::DrawTrajectory* and *G4VTrajectory::ShowTrajectory*.

Hits classes in examples /extended/analysis/A01 and /extended/runAndEvent/RE01 show how to do the same for your hits. The base class no-action methods CreateAttValues and GetAttDefs should be overridden in your concrete class. The comments in *G4VHit.hh* explain further.

In addition, the user is free to add a *G4std::vector<G4AttValue>** and a *G4std::vector<G4AttDef>** to a *G4VisAttributes* object as could, for example, be used by a *G4LogicalVolume* object.

At the time of writing, only the HepRep graphics systems are capable of displaying the G4AttValue information, but this information will become useful for all Geant4 visualization systems through improvements in release 8.1 or later.

8.7. Enhanced Trajectory Drawing

8.7.1. Default Configuration

Trajectory drawing styles are specified through trajectory drawing models. Each drawing model has a default configuration provided through a G4VisTrajContext object. The default context settings are shown below.

Property	**Default Setting**
Line colour	grey
Line visibility	true
Draw line	true
Draw auxiliary points	false
Auxiliary point type	squares
Auxiliary point size	2 pixels or mm*
Auxiliary point size type	screen
Auxiliary point fill style	filled
Auxiliary point colour	magenta
Auxiliary point visibility	true
Draw step point	false
Step point type	circles

Step point size	2 pixels or mm*
Step point size type	screen
Step point fill style	filled
Step point colour	yellow
Step point visibility	true
Time slice interval	0

* Depending on size type. If size type == screen, pixels are assumed and no unit need be supplied. If size type == world, a unit must be supplied, e.g., 10 cm.

Points to note:

- The context approach is intended to replace the configuration through the imode parameter. The use of imode is depreciated and will be removed in Geant4 v10.0.
- Different visualisation drivers handle trajectory configuration in different ways, so trajectories may not necessarily get displayed as you have configured them.

8.7.2. Trajectory Drawing Models

A trajectory drawing model can override the default context according to the properties of a given trajectory. The following models are supplied with the Geant4 distribution:

- G4TrajectoryGenericDrawer (generic)
- G4TrajectoryDrawByCharge (drawByCharge)
- G4TrajectoryDrawByParticleID (drawByParticleID)
- G4TrajectoryDrawByOriginVolume (drawByOriginVolume)
- G4TrajectoryDrawByAttribute (drawByAttribute)

Both the context and model properties can be configured by the user. The models are described briefly below, followed by some example configuration commands.

G4TrajectoryGenericDrawer

This model simply draws all trajectories in the same style, with the properties provided by the context.

G4TrajectoryDrawByCharge

This is the default model - if no model is specified by the user, this model will be constructed automatically. The trajectory lines are coloured according to charge, with all other configuration parameters provided by the default context. The default colouring scheme is shown below.

```
Charge          Colour
----------------------
1               Blue
-1              Red
0               Green
```

G4TrajectoryDrawByParticleID

This model colours trajectory lines according to particle type. All other configuration parameters are provided by the default context. By default, all trajectories are coloured grey. Chosen particle types can be highlighted with specified colours.

G4TrajectoryDrawByOriginVolume

This model colours trajectory lines according to the trajectories originating volume name. The volume can be either a logical or physical volume. Physical volume takes precedence over logical volume. All trajectories are coloured grey by default.

G4TrajectoryDrawByAttribute

This model draws trajectories based on the HepRep style attributes associated with trajectories. Each attribute drawer can be configured with interval and/or single value data. A new context object is created for each interval/single value. This makes it possible to have different step point markers etc, as well as line colour for trajectory attributes falling into different intervals, or matching single values. The single value data should override the interval data, allowing specific values to be highlighted. Units should be specified on the command line if the attribute unit is specified either as a G4BestUnit or if the unit is part of the value string.

8.7.3. Controlling from Commands

Multiple trajectory models can be created and configured using commands in the "`/vis/modeling/trajectories/`" directory. It is then possible to list available models and select one to be current.

Model configuration commands are generated dynamically when a model is instantiated. These commands apply directly to that instance. This makes it possible to have multiple instances of the drawByCharge model for example, each independently configurable through it's own set of commands.

See the interactive help for more information on the available commands.

8.7.3.1. Example commands

#Create a generic model named generic-0 by default

```
/vis/modeling/trajectories/create/generic
```

#Configure context to colour all trajectories red

```
/vis/modeling/trajectories/generic-0/default/setLineColour red
```

#Create a drawByCharge model named drawCharge-0 by default (Subsequent models will be named drawByCharge-1, drawByCharge-2, etc.)

```
/vis/modeling/trajectories/create/drawByCharge
```

#Create a drawByCharge model named testChargeModel

```
/vis/modeling/trajectories/create/drawByCharge testChargeModel
```

#Configure drawByCharge-0 model

```
/vis/modeling/trajectories/drawByCharge-0/set 1 red
/vis/modeling/trajectories/drawByCharge-0/set -1 red
/vis/modeling/trajectories/drawByCharge-0/set 0 white
```

#Configure testCharge model through G4Colour components

```
/vis/modeling/trajectories/testChargeModel/setRGBA 1 0 1 1 1
/vis/modeling/trajectories/testChargeModel/setRGBA -1 0.5 0.5 0.5 1
/vis/modeling/trajectories/testChargeModel/setRGBA 0 1 1 0 1
```

#Create a drawByParticleID model named drawByParticleID-0

```
/vis/modeling/trajectories/create/drawByParticleID
```

#Configure drawByParticleID-0 model

```
/vis/modeling/trajectories/drawByParticleID-0/set gamma red
/vis/modeling/trajectories/drawByParticleID-0/setRGBA e+ 1 0 1 1
```

#List available models

```
/vis/modeling/trajectories/list
```

#select drawByParticleID-0 to be current

```
/vis/modeling/trajectories/select drawByParticleID-0
```

#Create a drawByAttribute model named drawByAttribute-0

```
/vis/modeling/trajectories/create/drawByAttribute
```

#Configure drawByAttribute-0 model

```
/vis/modeling/trajectories/drawByAttribute-0/verbose true
```

#Select attribute "CPN"

```
/vis/modeling/trajectories/drawByAttribute-0/setAttribute CPN
```

#Configure single value data

```
/vis/modeling/trajectories/drawByAttribute-0/addValue brem_key  eBrem
/vis/modeling/trajectories/drawByAttribute-0/addValue annihil_key annihil
/vis/modeling/trajectories/drawByAttribute-0/addValue decay_key Decay
/vis/modeling/trajectories/drawByAttribute-0/addValue muIon_key muIoni
/vis/modeling/trajectories/drawByAttribute-0/addValue eIon_key  eIoni

/vis/modeling/trajectories/drawByAttribute-0/brem_key/setLineColour     red
/vis/modeling/trajectories/drawByAttribute-0/annihil_key/setLineColour  green
/vis/modeling/trajectories/drawByAttribute-0/decay_key/setLineColour    cyan
/vis/modeling/trajectories/drawByAttribute-0/eIon_key/setLineColour     yellow
/vis/modeling/trajectories/drawByAttribute-0/muIon_key/setLineColour magenta
```

#Create a drawByAttribute model named drawByAttribute-1

```
/vis/modeling/trajectories/create/drawByAttribute
```

#Select "IMag" attribute

```
/vis/modeling/trajectories/drawByAttribute-1/setAttribute IMag
```

#Configure interval data

```
/vis/modeling/trajectories/drawByAttribute-1/addInterval interval1 0.0 keV 2.5MeV
/vis/modeling/trajectories/drawByAttribute-1/addInterval interval2 2.5 MeV 5 MeV
/vis/modeling/trajectories/drawByAttribute-1/addInterval interval3 5 MeV 7.5 MeV
/vis/modeling/trajectories/drawByAttribute-1/addInterval interval4 7.5 MeV 10 MeV
/vis/modeling/trajectories/drawByAttribute-1/addInterval interval5 10 MeV 12.5 MeV
/vis/modeling/trajectories/drawByAttribute-1/addInterval interval6 12.5 MeV 10000 MeV

/vis/modeling/trajectories/drawByAttribute-1/interval1/setLineColourRGBA 0.8 0 0.8 1
/vis/modeling/trajectories/drawByAttribute-1/interval2/setLineColourRGBA 0.23 0.41 1 1
/vis/modeling/trajectories/drawByAttribute-1/interval3/setLineColourRGBA 0 1 0 1
/vis/modeling/trajectories/drawByAttribute-1/interval4/setLineColourRGBA 1 1 0 1
/vis/modeling/trajectories/drawByAttribute-1/interval5/setLineColourRGBA 1 0.3 0 1
/vis/modeling/trajectories/drawByAttribute-1/interval6/setLineColourRGBA 1 0 0 1
```

8.7.4. Controlling from Compiled Code

It is possible to use the enhanced trajectory drawing functionality in compiled code as well as from commands. Multiple trajectory models can be instantiated, configured and registered with G4VisManager. Only one model may be current. For example:

```
G4VisManager* visManager = new G4VisExecutive;
visManager->Initialize();

G4TrajectoryDrawByParticleID* model = new G4TrajectoryDrawByParticleID;
G4TrajectoryDrawByParticleID* model2 = new G4TrajectoryDrawByParticleID("test");

model->SetDefault("cyan");
model->Set("gamma", "green");
model->Set("e+", "magenta");
model->Set("e-", G4Colour(0.3, 0.3, 0.3));

visManager->RegisterModel(model);
visManager->RegisterModel(model2);

visManager->SelectTrajectoryModel(model->Name());
```

8.7.5. Drawing by time

To draw by time, you need to use G4RichTrajectory, for example:

```
/vis/scene/add/trajectories rich
```

or

```
/vis/scene/add/trajectories rich smooth
```

When you run, you need to create a trajectory model and set the time slice interval (remembering that paticles are often relativistic and travel 30 cm/ns):

```
/vis/modeling/trajectories/create/drawByCharge
/vis/modeling/trajectories/drawByCharge-0/default/setDrawStepPts true
/vis/modeling/trajectories/drawByCharge-0/default/setStepPtsSize 5
/vis/modeling/trajectories/drawByCharge-0/default/setDrawAuxPts true
/vis/modeling/trajectories/drawByCharge-0/default/setAuxPtsSize 5
/vis/modeling/trajectories/drawByCharge-0/default/setTimeSliceInterval 0.1 ns
/vis/modeling/trajectories/list
```

and use a graphics driver that can display by time:

```
/vis/open OGLSX
/vis/drawVolume
/vis/scene/add/trajectories rich
/vis/ogl/set/startTime 0.5 ns
/vis/ogl/set/endTime 0.8 ns
/run/beamOn
/vis/viewer/refresh
```

A good way to see the particles moving through the detector is:

```
/vis/ogl/set/fade 1
/vis/ogl/set/displayHeadTime true
/control/alias timeRange 1
/control/loop movie.loop -{timeRange} 40 0.1
```

where `fade` gives a vapour-trail effect, `displayHeadTime` displays the time of the leading edge as 2D text, and `movie.loop` is a macro file:

```
/vis/ogl/set/startTime {startTime} ns {timeRange} ns
```

From there, it's straightforward to Section 8.10 make a movie.

8.8. Trajectory Filtering

Trajectory filtering allows you to visualise a subset of available trajectories. This can be useful if you only want to view interesting trajectories and discard uninteresting ones. Trajectory filtering can be run in two modes:

- **Soft filtering**: In this mode, uninteresting trajectories are marked invisible. Hence, they are still written, but (depending on the driver) will not be displayed. Some drivers, for example the HepRepFile driver, will allow you to selectively view these soft filtered trajectories
- **Hard filtering**: In this mode, uninteresting trajectories are not drawn at all. This mode is especially useful if the job produces huge graphics files, dominated by data from uninteresting trajectories.

Trajectory filter models are used to apply filtering according to specific criteria. The following models are currently supplied with the Geant4 distribution:

- G4TrajectoryChargeFilter (chargeFilter)
- G4TrajectoryParticleFilter (particleFilter)
- G4TrajectoryOriginVolumeFilter (originVolumeFilter)
- G4TrajectoryAttributeFilter (attributeFilter)

Multiple filters are automatically chained together, and can configured either interactively or in commands or in compiled code. The filters can be inverted, set to be inactive or set in a verbose mode. The above models are described briefly below, followed by some example configuration commands.

G4TrajectoryChargeFilter

This model filters trajectories according to charge. In standard running mode, only trajectories with charges matching those registered with the model will pass the filter.

G4TrajectoryParticleFilter

This model filters trajectories according to particle type. In standard running mode, only trajectories with particle types matching those registered with the model will pass the filter.

G4TrajectoryOriginVolumeFilter

This model filters trajectories according to originating volume name. In standard running mode, only trajectories with originating volumes matching those registered with the model will pass the filter.

G4TrajectoryAttributeFilter

This model filters trajectories based on the HepRep style attributes associated with trajectories. Each attribute drawer can be configured with interval and/or single value data. Single value data should override the interval data. Units should be specified on the command line if the attribute unit is specified either as a G4BestUnit or if the unit is part of the value string.

8.8.1. Controlling from Commands

Multiple trajectory filter models can be created and configured using commands in the "`/vis/filtering/trajectories/`" directory. All generated filter models are chained together automatically.

Model configuration commands are generated dynamically when a filter model is instantiated. These commands apply directly to that instance.

See the interactive help for more information on the available commands.

8.8.2. Example commands

#Create a particle filter. Configure to pass only gammas. Then

#invert to pass anything other than gammas. Set verbose printout,

#and then deactivate filter

```
/vis/filtering/trajectories/create/particleFilter
/vis/filtering/trajectories/particleFilter-0/add gamma
/vis/filtering/trajectories/particleFilter-0/invert true
/vis/filtering/trajectories/particleFilter-0/verbose true
/vis/filtering/trajectories/particleFilter-0/active false
```

#Create a charge filter. Configure to pass only neutral trajectories.

#Set verbose printout. Reset filter and reconfigure to pass only

#negativly charged trajectories.

```
/vis/filtering/trajectories/create/chargeFilter
/vis/filtering/trajectories/chargeFilter-0/add 0
/vis/filtering/trajectories/chargeFilter-0/verbose true
/vis/filtering/trajectories/chargeFilter-0/reset true
/vis/filtering/trajectories/chargeFilter-0/add -1
```

#Create an attribute filter named attributeFilter-0

```
/vis/filtering/trajectories/create/attributeFilter
```

#Select attribute "IMag"

```
/vis/filtering/trajectories/attributeFilter-0/setAttribute IMag
```

#Select trajectories with 2.5 MeV <= IMag< 1000 MeV

```
/vis/filtering/trajectories/attributeFilter-0/addInterval 2.5 MeV 1000 MeV
```

#List filters

```
/vis/filtering/trajectories/list
```

#Note that although particleFilter-0 and chargeFilter-0 are automatically

#chained, particleFilter-0 will not have any effect since

#it is has been deactivated.

8.8.3. Hit Filtering

The attribute based filtering can be used on hits as well as trajectories. To active the interactive attribute based hit filtering, a filter call should be added to the "Draw" method of the hit class:

```
  void MyHit::Draw()
  {
     ...
     if (! pVVisManager->FilterHit(*this)) return;
     ...
  }
```

Interactive filtering can then be done through the commands in `/vis/filtering/hits`.

8.9. Polylines, Markers and Text

Polylines, markers and text are defined in the `graphics_reps` category, and are used only for visualization. Here we explain their definitions and usages.

8.9.1. Polylines

A polyline is a set of successive line segments. It is defined with a class *G4Polyline* defined in the `graphics_reps` category. A polyline is used to visualize tracking steps, particle trajectories, coordinate axes, and any other user-defined objects made of line segments.

G4Polyline is defined as a list of *G4Point3D* objects, i.e., vertex positions. The vertex positions are set to a *G4Polyline* object with the `push_back()` method.

For example, an x-axis with length 5 cm and with red color is defined in Example 8.5.

Example 8.5. Defining an x-axis with length 5 cm and with colour red.

```
 //----- C++ source codes: An example of defining a line segment
// Instantiate an emply polyline object
G4Polyline  x_axis;

// Set red line colour
G4Colour         red(1.0, 0.0, 0.0);
G4VisAttributes  att(red);
x_axis.SetVisAttributes(&att);

// Set vertex positions
x_axis.push_back( G4Point3D(0., 0., 0.) );
x_axis.push_back( G4Point3D(5.*cm, 0., 0.) );

 //----- end of C++ source codes
```

8.9.2. Markers

Here we explain how to use 3D markers in Geant4 Visualization.

What are Markers?

Markers set marks at arbitrary positions in the 3D space. They are often used to visualize hits of particles at detector components. A marker is a 2-dimensional primitive with shape (square, circle, etc), color, and special properties (a) of always facing the camera and (b) of having the possibility of a size defined in screen units (pixels). Here "size" means "overall size", e.g., diameter of circle and side of square (but diameter and radius access functions are defined to avoid ambiguity).

So the user who constructs a marker should decide whether or not it should be visualized to a given size in world coordinates by setting the world size. Alternatively, the user can set the screen size and the marker is visualized to its screen size. Finally, the user may decide not to set any size; in that case, it is drawn according to the sizes specified in the default marker specified in the class *G4ViewParameters*.

By default, "square" and "circle" are supported in Geant4 Visualization. The former is described with class *G4Square*, and the latter with class *G4Circle*:

Marker Type	**Class Name**
circle	*G4Circle*
right square	*G4Square*

These classes are inherited from class *G4VMarker*. They have constructors as follows:

```
    //----- Constructors of G4Circle and G4Square
    G4Circle::G4Circle (const G4Point3D& pos );
    G4Square::G4Square (const G4Point3D& pos);
```

Access functions of class *G4VMarker* are summarized below.

Access functions of markers

Example 8.6 shows the access functions inherited from the base class *G4VMarker*.

Example 8.6. The access functions inherited from the base class *G4VMarker*.

```
//----- Set functions of G4VMarker
void G4VMarker::SetPosition( const G4Point3D& );
void G4VMarker::SetWorldSize( G4double );
void G4VMarker::SetWorldDiameter( G4double );
void G4VMarker::SetWorldRadius( G4double );
void G4VMarker::SetScreenSize( G4double );
void G4VMarker::SetScreenDiameter( G4double );
void G4VMarker::SetScreenRadius( G4double );
void G4VMarker::SetFillStyle( FillStyle );
// Note: enum G4VMarker::FillStyle {noFill, hashed, filled};

//----- Get functions of G4VMarker
G4Point3D G4VMarker::GetPosition () const;
G4double G4VMarker::GetWorldSize () const;
G4double G4VMarker::GetWorldDiameter () const;
G4double G4VMarker::GetWorldRadius () const;
G4double G4VMarker::GetScreenSize () const;
G4double G4VMarker::GetScreenDiameter () const;
G4double G4VMarker::GetScreenRadius () const;
FillStyle G4VMarker::GetFillStyle () const;
// Note: enum G4VMarker::FillStyle {noFill, hashed, filled};
```

Example 8.7 shows sample C++ source code to define a very small red circle, i.e., a dot with diameter 1.0 pixel. Such a dot is often used to visualize a hit.

Example 8.7. Sample C++ source code to define a very small red circle.

```
//----- C++ source codes: An example of defining a red small maker
G4Circle circle(position); // Instantiate a circle with its 3D
                           // position. The argument "position"
                           // is defined as G4Point3D instance
circle.SetScreenDiameter (1.0); // Should be circle.SetScreenDiameter
                                //  (1.0 * pixels) - to be implemented
circle.SetFillStyle (G4Circle::filled); // Make it a filled circle
G4Colour colour(1.,0.,0.);              // Define red color
G4VisAttributes attribs(colour);        // Define a red visualization attribute
circle.SetVisAttributes(attribs);       // Assign the red attribute to the circle
//----- end of C++ source codes
```

8.9.3. Text

Text, i.e., a character string, is used to visualize various kinds of description, particle name, energy, coordinate names etc. Text is described by the class *G4Text* . The following constructors are supported:

```
    //----- Constructors of G4Text
    G4Text (const G4String& text);
    G4Text (const G4String& text, const G4Point3D& pos);
```

where the argument `text` is the text (string) to be visualized, and `pos` is the 3D position at which the text is visualized.

Text is currently drawn only by the OpenGL drivers, such as OGLIX, OGLIXm, OGLIQt and OpenInventor. It is not yet supported on other drivers, including the Windows OpenGL drivers, HepRep, etc.

Note that class *G4Text* also inherits *G4VMarker*. Size of text is recognized as "font size", i.e., height of the text. All the access functions defined for class *G4VMarker* mentioned above are available. In addition, the following access functions are available, too:

```
    //----- Set functions of G4Text
    void G4Text::SetText ( const G4String& text ) ;
    void G4Text::SetOffset ( double dx, double dy ) ;

    //----- Get functions of G4Text
    G4String G4Text::GetText () const;
    G4double G4Text::GetXOffset () const;
    G4double G4Text::GetYOffset () const;
```

Method `SetText()` defines text to be visualized, and `GetText()` returns the defined text. Method `SetOffset()` defines x (horizontal) and y (vertical) offsets in the screen coordinates. By default, both offsets are zero, and the text starts from the 3D position given to the constructor or to the method `G4VMarker:SetPosition()`. Offsets should be given with the same units as the one adopted for the size, i.e., world-size or screen-size units.

Example 8.8 shows sample C++ source code to define text with the following properties:

- Text: "Welcome to Geant4 Visualization"
- Position: (0.,0.,0.) in the world coordinates
- Horizontal offset: 10 pixels
- Vertical offset: -20 pixels
- Colour: blue (default)

Example 8.8. An example of defining text.

```
//----- C++ source codes: An example of defining a visualizable text

//----- Instantiation
G4Text text ;
text.SetText ( "Welcome to Geant4 Visualization");
text.SetPosition ( G4Point3D(0.,0.,0.) );
// These three lines are equivalent to:
//  G4Text text ( "Welcome to Geant4 Visualization",
//                G4Point3D(0.,0.,0.) );

//----- Size (font size in units of pixels)
G4double fontsize = 24.; // Should be 24. * pixels - to be implemented.
text.SetScreenSize ( fontsize );

//----- Offsets
G4double x_offset = 10.; // Should be 10. * pixels - to be implemented.
G4double y_offset = -20.; // Should be -20. * pixels - to be implemented.
text.SetOffset( x_offset, y_offset );

//----- Color (Blue is the default setting, and so the codes below are omissible)
G4Colour blue( 0., 0., 1. );
G4VisAttributes att ( blue );
text.SetVisAttributes ( att );

//----- end of C++ source codes
```

8.10. Making a Movie

These instructions are suggestive only. The following procedures have not been tested on all platforms. There are clearly some instructions that apply only to Unix-like systems with an X-Windows based windowing system. However, it should not be difficult to take the ideas presented here and extend them to other platforms and systems.

The procedures described here need graphics drivers that can produce picture files that can be converted to a form suitable for an MPEG encoder. There may be other ways of capturing the screen images and we would be happy to hear about them. Graphics drivers currently capable of producing picture files are: More informations about MPEG encoder

Driver	File type

DAWNFILE	prim then eps using **dawn**
HepRepFile	HepRep1
HepRep	HepRep2
OGLX	eps
Qt	jpeg, eps, ppm, ...
RayTracer	jpeg
VRMLFILE	vrml

So far, only DAWNFILE, OGLX and RayTracer have been "road tested". Once in a standard format, such as eps, the **convert** program from ImageMagick can convert to ppm files suitable for **mpeg2encode**.

8.10.1. OGLX

Make a macro something like this:

```
/control/verbose 2
/vis/open OGLSX 600x600-0+0
/vis/drawVolume
/vis/viewer/reset
/vis/viewer/set/style surface
/vis/viewer/set/projection perspective 50 deg
/control/alias phi 30
/control/loop movie.loop theta 0 360 1
```

which invokes movie.loop, which is something like:

```
/vis/viewer/set/viewpointThetaPhi {theta} {phi}
/vis/viewer/zoom 1.005
/vis/ogl/printEPS
```

This produces lots of eps files. Then...

```
make_mpeg2encode_parfile.sh G4OpenGL_*eps
```

Then edit mpeg2encode.par to specify file type and size, etc.:

```
$ diff mpeg2encode.par~ mpeg2encode.par
7c7
< 1         /* input picture file format: 0=*.Y,*.U,*.V, 1=*.yuv, 2=*.ppm */
---
> 2         /* input picture file format: 0=*.Y,*.U,*.V, 1=*.yuv, 2=*.ppm */
15,17c15,17
<    /* horizontal_size */
<   /* vertical_size */
< 8         /* aspect_ratio_information 1=square pel, 2=4:3, 3=16:9, 4=2.11:1 */
---
> 600   /* horizontal_size */
> 600  /* vertical_size */
> 1         /* aspect_ratio_information 1=square pel, 2=4:3, 3=16:9, 4=2.11:1 */
```

Then convert to ppm:

```
for i in G4OpenGL*eps;
  do j=`basename $i .eps`; command="convert $i $j.ppm"; echo $command; $command; done
```

Then

```
mpeg2encode mpeg2encode.par G4OpenGL.mpg
```

Then, on Mac, for example:

```
open G4OpenGL.mpg
```

opens a QuickTime player.

8.10.2. Qt

The Qt driver provides one of the easiest ways to make a movie. Of course, you first need to add the Qt libraries and link with Qt, but once you have that, Qt provides a ready-made function to store all updates of the OpenGL frame into the movie format. You then use loops (as defined in OGLX section above) or even move/rotate/zoom you scene by mouse actions to form your movie.

The Qt driver automatically handles all of the movie-making steps described in the OGLX section of this document - storing the files, converting them and assembling the finished movie. You just have to take care of installing an mpeg_encoder.

To make a movie :

- Right click to display a context menu, "Action"->"Movie parameters".
- Select MPEG encoder path if it was not found.
- Select the name of the output movie.
- Let go! Hit SPACE to Start/Pause recording, RETURN to STOP

Then, open your movie (on Mac, for example):

```
open G4OpenGL.mpg
```

opens a QuickTime player.

8.10.3. DAWNFILE

You need to invoke **dawn** in "direct" mode, which picks up parameters from .DAWN_1.history, and suppress the GUI:

```
alias dawn='dawn -d'
export DAWN_BATCH=1
```

Change OGLSX to DAWNFILE in the above set of Geant4 commands and run. Then convert to ppm files as above:

```
for i in g4_*.eps;
  do j=`basename $i .eps`; command="convert $i $j.ppm"; echo $command; $command; done
```

Then make a .par file:

```
make_mpeg2encode_parfile.sh g4_*ppm
```

and edit mpeg2encode.par:

```
$ diff mpeg2encode.par~ mpeg2encode.par
7c7
< 1         /* input picture file format: 0=*.Y,*.U,*.V, 1=*.yuv, 2=*.ppm */
---
> 2         /* input picture file format: 0=*.Y,*.U,*.V, 1=*.yuv, 2=*.ppm */
9c9
< 1         /* number of first frame */
---
> 0         /* number of first frame */
15,16c15,16
<    /* horizontal_size */
<   /* vertical_size */
---
```

```
> 482   /* horizontal_size */
> 730  /* vertical_size */
```

Then encode and play:

```
mpeg2encode mpeg2encode.par DAWN.mpg
open DAWN.mpg
```

8.10.4. RayTracerX

```
/control/verbose 2
/vis/open RayTracerX 600x600-0+0
# (Raytracer doesn't need a scene; smoother not to /vis/drawVolume.)
/vis/viewer/reset
/vis/viewer/set/style surface
/vis/viewer/set/projection perspective 50 deg
/control/alias phi 30
/control/loop movie.loop theta 0 360 1
```

where movie.loop is as above. This produces lots of jpeg files (but takes 3 days!!!). Then...

```
make_mpeg2encode_parfile.sh g4RayTracer*jpeg
```

Then edit mpeg2encode.par to specify file type and size, etc.:

```
$ diff mpeg2encode.par.orig mpeg2encode.par
7c7
< 1         /* input picture file format: 0=*.Y,*.U,*.V, 1=*.yuv, 2=*.ppm */
---
> 2         /* input picture file format: 0=*.Y,*.U,*.V, 1=*.yuv, 2=*.ppm */
15,17c15,17
<    /* horizontal_size */
<   /* vertical_size */
< 8         /* aspect_ratio_information 1=square pel, 2=4:3, 3=16:9, 4=2.11:1 */
---
> 600   /* horizontal_size */
> 600  /* vertical_size */
> 1         /* aspect_ratio_information 1=square pel, 2=4:3, 3=16:9, 4=2.11:1 */
```

Then convert to ppm, encode and play:

```
for i in g4*jpeg;
  do j=`basename $i .jpeg`; command="convert $i $j.ppm"; echo $command; $command; done
mpeg2encode mpeg2encode.par g4RayTracer.mpg
open g4RayTracer.mpg
```

Chapter 9. Examples

9.1. Novice Examples

The Geant4 toolkit includes several fully coded examples which demonstrate the implementation of the user classes required to build a customized simulation. Seven "novice" examples are provided ranging from the simulation of a non-interacting particle and a trivial detector, to the simulation of electromagnetic and hadronic physics processes in a complex detector. Each example may be used as a base from which more detailed applications can be developed. A set of "extended" examples implement simulations of actual high energy physics detectors and require some libraries in addition to those of Geant4. The "advanced" examples cover cases useful to the developement of the Geant4 toolkit itself.

The examples can be compiled and run without modification. Most of them can be run both in interactive and batch mode using the input macro files (`*.in`) and reference output files (`*.out`) provided. These examples are run routinely as part of the validation, or testing, of official releases of the Geant4 toolkit.

9.1.1. Novice Example Summary

Descriptions of the 7 novice examples are provided here along with links to the code.

`ExampleN01` (Description below)

- Mandatory user classes
- Demonstrates how Geant4 kernel works

`ExampleN02` (Description below)

- Simplified tracker geometry with uniform magnetic field
- Electromagnetic processes

`ExampleN03` (Description below)

- Simplified calorimeter geometry
- Electromagnetic processes
- Various materials

`ExampleN04` (Description below)

- Simplified collider detector with a readout geometry
- Full ``ordinary" processes
- PYTHIA primary events
- Event filtering by stack

`ExampleN05` (Description below)

- Simplified BaBar calorimeter
- EM shower parametrisation

`ExampleN06` (Description below)

- Optical photon processes

`ExampleN07` (Description below)

- Geometrical Regions for production thresholds

- Dynamic geometry setups between runs
- Primitive scorer and filter
- Derived run class and run action

Table 9.1, Table 9.2 and Table 9.3 display the ``item charts'' for the examples currently prepared in the novice level.

	`ExampleN01`	`ExampleN02`	`ExampleN03`
comments	minimal set for geantino transportation	fixed target tracker geometry	EM shower in calorimeter
Run	`main()` for hard coded batch	`main()` for interactive mode	• `main()` for interactive mode • SetCut and Process On/Off
Event	event generator selection (particleGun)	event generator selection (particleGun)	• event generator selection (particleGun) • ``end of event'' simple analysis in *UserEventAction*
Tracking	hard coded verbose level setting	selecting secondaries	select trajectories
Geometry	geometry definition (CSG)	• geometry definition (includes Parametrised volume) • uniform magnetic field	• geometry definition (includes replica) • uniform magnetic field
Hits/Digi	-	tracker type hits	calorimeter-type hits
PIIM	• minimal particle set • single element material	• EM particles set • mixtures and compound elements	• EM particles set • mixtures and compound elements
Physics	transportation	EM physics	EM physics
Vis	-	• detector & trajectory drawing • tracker type hits drawing	detector & trajectory drawing
(G)UI	-	GUI selection	GUI selection
Global	-	-	-

Table 9.1. The ``item chart'' for novice level examples `N01`, `N02` and `N03`.

	ExampleN04	ExampleN05	ExampleN06
comments	simplified collider geometry	parametrised shower example	Optical photon example
Run	main() for interactive mode	main() for interactive mode	main() for interactive mode
Event	• event generator selection (HEPEvtInterface) • Stack control	event generator selection (HEPEvtInterface)	event generator selection (particleGun)
Tracking	• select trajectories • selecting secondaries	-	-
Geometry	• geometry definition (includes Param/Replica) • non-uniform magnetic field	ghost volume for shower parametrisation	geometry definition (BREP with rotation)
Hits/Digi	• Tracker/calorimeter/counter types • ReadOut geometry	Sensitive detector for shower parametrisation	-
PIIM	• Full particle set • mixtures and compound elements	• EM set • mixtures and compound elements	• EM set • mixtures and compound elements
Physics	Full physics processes	Parametrized shower	Optical photon processes
Vis	• detector & hit drawing • calorimeter type hits drawing	detector & hit drawing	-
(G)UI	define user commands	define user commands	define user commands
Global	-	-	random number engine

Table 9.2. The ``item chart'' for novice level examples N04, N05, and N06.

	ExampleN07
comments	Cuts per region
Run	• main() for interactive mode • Customized run class
Event	event generator selection (particleGun)
Tracking	-
Geometry	• geometry definition (includes Replica) • Region
Hits/Digi	• Primitive scorer • Filter
PIIM	• EM set • mixtures and compound elements
Physics	EM processes
Vis	detector & trajectory drawing
(G)UI	define user commands
Global	-

Table 9.3. The ``item chart'' for novice level example N07.

9.1.2. Example N01

Basic concepts

- minimal set for geantino transportation

Classes

`main()` (source file)

- hard coded batch
- construction and deletion of *G4RunManager*
- hard coded verbose level setting to *G4RunManager*, *G4EventManager* and *G4TrackingManager*
- construction and set of mandatory user classes
- hard coded `beamOn()`
- Hard coded UI command application

ExN01DetectorConstruction

(header file) (source file)

- derived from G4VUserDetectorConstruction
- definitions of single element materials
- CSG solids
- *G4PVPlacement* without rotation

ExN01PhysicsList

(header file) (source file)

- derived from *G4VUserPhysicsList*
- definition of geantino
- assignment of transportation process

ExN01PrimaryGeneratorAction

(header file) (source file)

- derived from *G4VPrimaryGeneratorAction*
- construction of *G4ParticleGun*
- primary event generation via particle gun

9.1.3. Example N02

Basic concepts

- Detector: fixed target type
- Processes: EM
- Hits: tracker type hits

Classes

`main()` (source file)

- `main()` for interactive mode (and batch mode via macro file)
- construction and deletion of (G)UI session and *VisManager*
- random number engine
- construction and deletion of *G4RunManager*
- construction and set of mandatory user classes

ExN02DetectorConstruction

(header file) (source file)

- derived from *G4VUserDetectorConstruction*
- definitions of single-element, mixture and compound materials
- CSG solids
- Uniform magnetic field: construction of *ExN02MagneticField*
- Physical Volumes
  - *G4Placement* volumes with & without rotation.
  - *G4PVParameterised* volumes without rotation

ExN02MagneticField

(header file) (source file)

- derived from *G4MagneticField*
- Uniform field. *ExN02MagneticField*

ExN02PhysicsList

(header file) (source file)

- derived from *G4VUserPhysicsList*
- definition of geantinos, electrons, positrons, gammas
- utilisation of transportation and 'standard' EM-processes
- Interactivity: chooses processes interactively (=> messenger class)

ExN02PrimaryGeneratorAction

(header file) (source file)

- derived from *G4VPrimaryGeneratorAction*
- construction of *G4ParticleGun*
- primary event generation via particle gun

ExN02RunAction

(header file) (source file)

- derived from *G4VUserRunAction*
- draw detector

ExN02EventAction

(header file) (source file)

- derived from *G4VUserEventAction*
- print time information

ExN02TrackerSD

(header file) (source file)

- derived from *G4VSensitiveDetector*
- tracker-type hit generation

ExN02TrackerHit

(header file) (source file)

- derived from *G4VHit*
- draw hit point

9.1.4. Example N03

Basic concepts

- Visualize Em processes.
- Interactivity: build messenger classes.
- Gun: shoot particle randomly.
- Tracking: collect energy deposition, total track length

Classes

`main()` (source file)

- `main()` for interactive mode and batch mode via macro file
- construction and deletion of *G4RunManager*
- construction and deletion of (G)UI session and *VisManager*
- construction and set of mandatory user classes
- automatic initialization of geometry and visualization via a macro file

ExN03DetectorConstruction

(header file) (source file)

- derived from *G4VUserDetectorConstruction*
- definitions of single materials and mixtures
- CSG solids
- *G4PVPlacement* without rotation
- Interactivity: change detector size, material, magnetic field. (=>messenger class)
- visualization

ExN03PhysicsList

(header file) (source file)

- derived from *G4VUserPhysicsList*
- definition of geantinos, gamma, leptons, light mesons barions and ions
- Transportation process, 'standard' Em processes, Decay
- Interactivity: *SetCut*, process on/off. (=> messenger class)

ExN03PrimaryGeneratorAction

(header file) (source file)

- derived from *G4VPrimaryGeneratorAction*
- construction of *G4ParticleGun*
- primary event generation via particle gun
- Interactivity: shoot particle randomly. (=> messenger class)

ExN03RunAction

(header file) (source file)

- derived from *G4VUserRunAction*
- draw detector and tracks
- Interactivity: *SetCut*, process on/off.
- Interactivity: change detector size, material, magnetic field.

ExN03EventAction

(header file) (source file)

- derived from *G4VUserEventAction*
- store trajectories
- print end of event information (energy deposited, etc.)

ExN03SteppingAction

(header file) (source file)

- derived from *G4VUserSteppingAction*
- collect energy deposition, etc.

9.1.5. Example N04

Basic concepts

- Simplified collider experiment geometry
- Full hits/digits/trigger

Classes

`main()` (source file)

- construction and deletion of *ExN04RunManager*
- construction and deletion of (G)UI session and *VisManager*
- construction and set of user classes

ExN04DetectorConstruction

(header file) (source file)

- derived from *G4VUserDetectorConstruction*
- construction of *ExN04MagneticField*
- definitions of mixture and compound materials
- material-dependent CutOff
- simplified collider geometry with Param/Replica
- tracker/muon -- parametrised
- calorimeter -- replica

ExN04TrackerParametrisation

(header file) (source file)

- derived from *G4VPVParametrisation*
- parametrised sizes

ExN04CalorimeterParametrisation

(header file) (source file)

- derived from *G4VPVParametrisation*
- parametrized position/rotation

ExN04MagneticField

(header file) (source file)

- derived from *G4MagneticField*
- solenoid and toroidal fields

ExN04TrackerSD

(header file) (source file)

- derived from *G4VSensitiveDetector*
- tracker-type hit generation

ExN04TrackerHit

(header file) (source file)

- derived from *G4VHit*
- draw hit point

ExN04CalorimeterSD

(header file) (source file)

- derived from *G4VSensitiveDetector*
- calorimeter-type hit generation

ExN04CalorimeterHit

(header file) (source file)

- derived from *G4VHit*
- draw physical volume with variable color

ExN04MuonSD

(header file) (source file)

- derived from *G4VSensitiveDetector*
- Scintillator-type hit generation

ExN04MuonHit

(header file) (source file)

- derived from *G4VHit*
- draw physical volume with variable color

ExN04PrimaryGeneratorAction

(header file) (source file)

- derived from *G4VPrimaryGeneratorAction*
- construction of *G4HEPEvtInterface*
- primary event generation with PYTHIA event

ExN04EventAction

(header file) (source file)

- store the initial seeds

ExN04StackingAction

(header file) (source file)

- derived from *G4UserStackingAction*
- ``stage'' control and priority control

- event abortion

ExN04StackingActionMessenger

(header file) (source file)

- derived from *G4UImessenger*
- define abortion conditions

ExN04TrackingAction

(header file) (source file)

- derived from *G4UserTrackingAction*
- select trajectories
- select secondaries

9.1.6. Example N05

Basic concepts

- Use of shower parameterisation:
  - definition of an EM shower model
  - assignment to a Logical Volume
  - (definition of ghost volume when ready)
- Interactivity: build of messengers classes
- Hits/Digi: filled from detailed and parameterised simulation (calorimeter type hits ?)

Classes

`main()` (source file)

- `main()` for interactive mode
- construction and deletion of *G4RunManager*
- construction and set of mandatory user classes
- construction of the *G4GlobalFastSimulationmanager*
- construction of a *G4FastSimulationManager* to assign fast simulation model to a logical volume (envelope)
- (definition of ghost volume for parameterisation)
- construction EM physics shower fast simulation model

ExN05EMShowerModel

(header file) (source file)

- derived from *G4VFastSimulationModel*
- energy deposition in sensitive detector

ExN05PionShowerModel

(header file) (source file)

- derived from *G4VFastSimulationModel*
- energy deposition in sensitive detector

ExN05DetectorConstruction

(header file) (source file)

- derived from *G4VUserDetectorConstruction*
- definitions of single materials and mixtures
- CSG solids

- *G4PVPlacement*

ExN05PhysicsList

(header file) (source file)

- derived from *G4VUserPhysicsList*
- assignment of *G4FastSimulationManagerProcess*

ExN05PrimaryGeneratorAction

(header file) (source file)

- derived from *G4VPrimaryGeneratorAction*
- construction of *G4ParticleGun*
- primary event generation via particle gun

ExN05RunAction

(header file) (source file)

- derived from *G4VUserRunAction*
- draw detector
- (activation/deactivation of parameterisation ?)

ExN05EventAction

(header file) (source file)

- derived from *G4VUserEventAction*
- print time information

9.1.7. Example N06

Basic concepts

- Interactivity : build messenger classes.
- Event : Gun, shoot charge particle at Cerenkov Radiator and Scintillator.
- PIIM : material/mixture with optical and scintillation properties.
- Geometry : volumes filled with optical materials and possessing surface properties.
- Physics : define and initialize optical processes.
- Tracking : generate Cerenkov radiation, collect energy deposition to produce scintillation.
- Hits/Digi : PMT as detector.
- Visualization : geometry, optical photon trajectories.

Classes

`main()` (source file)

- `main()` for interactive mode and batch mode via macro file
- random number engine
- construction and deletion of *G4RunManager*
- construction and set of mandatory user classes
- hard coded `beamOn`

ExN06DetectorConstruction

(header file) (source file)

- derived from *G4VUserDetectorConstruction*
- definitions of single materials and mixtures

- generate and add Material Properties Table to materials
- CSG and BREP solids
- *G4PVPlacement* with rotation
- definition of surfaces
- generate and add Material Properties Table to surfaces
- visualization

ExN06PhysicsList

(header file) (source file)

- derived from *G4VUserPhysicsList*
- definition of gamma, leptons and optical photons
- transportation, 'standard' EM-processes, decay, Cerenkov, scintillation, 'standard' optical and boundary process
- modify/augment optical process parameters

ExN06PrimaryGeneratorAction

(header file) (source file)

- derived from *G4VPrimaryGeneratorAction*
- construction of *G4ParticleGun*
- primary event generation via particle gun

ExN06RunAction

(header file) (source file)

- derived from *G4VUserRunAction*
- draw detector

9.1.8. Example N07

Basic concepts

- Geometry : Changing geometry of three simplified sandwitch calorimeters without re-building a world volume.
- Region : Defining geometrical regions ans setting production thresholds for each region.
- Run : Utilizing a concrete run class derived from G4Run base class for accumulating physics quantities and hits as a run.
- Hits : Demonstrating the use of primitive scorer and filter classes without implementing sensitive detector class.

Classes

`main()` (source file)

- `main()` for interactive mode and batch mode via macro file
- construction and deletion of *G4RunManager*
- construction and deletion of *G4VisExective* and *G4UITerminal*
- construction and set of mandatory user classes
- construction and set of *ExN07RunAction*

ExN07DetectorConstruction

(header file) (source file)

- derived from *G4VUserDetectorConstruction*
- definitions of materials and mixtures
- *G4Box* with *G4PVPlacement* and *G4PVReplica*
- Dynamic changing of size, position, orientation and number of volumes
- *G4Region* for each calorimeter tower

- *G4VPrimitiveScorer* and *G4VSDFilter*
- visualization

ExN07DetectorMessenger

(header file) (source file)

- derived from *G4UIMessenger*
- definition of example-specific geometry commands

ExN07PhysicsList

(header file) (source file)

- derived from *G4VUserPhysicsList*
- difine all types of particles
- define standard EM and decay processes
- production thresholds for each region

ExN07PrimaryGeneratorAction

(header file) (source file)

- derived from *G4VPrimaryGeneratorAction*
- construction of *G4ParticleGun*
- primary event generation via particle gun

ExN07RunAction

(header file) (source file)

- derived from *G4UserRunAction*
- constructing *ExN07Run* class object
- print out a run summary with *ExN07Run* class object

ExN07Run

(header file) (source file)

- derived from *G4Run*
- uses *G4THitsMap* template class to accumulate physics quantities
- extracts event data from *G4Event* and add up to run data

9.2. Extended Examples

9.2.1. Extended Example Summary

Geant4 extended examples serve three purposes:

- testing and validation of processes and tracking,
- demonstration of Geant4 tools, and
- extending the functionality of Geant4.

The code for these examples is maintained as part of the categories to which they belong. Links to descriptions of the examples are listed below.

9.2.1.1. Analysis

- A01 - hit-scoring and histogramming using the AIDA interface
- AnaEx01 - histogram and tuple manipulations using an AIDA compliant system

- N03Con - modified novice example N03 showing how to use a Convergence Tester

9.2.1.2. Electromagnetic

- TestEm0 - how to print cross-sections and stopping power used in input by the standard EM package
- TestEm1 - how to count processes, activate/inactivate them and survey the range of charged particles. How to define a maximum step size
- TestEm2 - shower development in an homogeneous material : longitudinal and lateral profiles
- TestEm3 - shower development in a sampling calorimeter : collect energy deposited, survey energy flow and print stopping power
- TestEm4 - 9 MeV point like photon source: plot spectrum of energy deposited in a single media
- TestEm5 - how to study transmission, absorption and reflection of particles through a single, thin or thick, layer.
- TestEm6 - physics list for rare, high energy, electromagnetic processes: gamma conversion and e+ annihilation into pair of muons
- TestEm7 - how to produce a Bragg curve in water phantom. How to compute dose in tallies
- TestEm8 - test of photo-absorption-ionisation model in thin absorbers, and transition radiation
- TestEm9 - shower development in a crystal calorimeter; cut-per-region
- TestEm10 - XTR transition radiation model, investigation of ionisation in thin absorbers
- TestEm11 - how to plot a depth dose profile in a rectangular box
- TestEm12 - how to plot a depth dose profile in spherical geometry : point like source
- TestEm13 - how to compute cross sections of EM processes from rate of transmission coefficient
- TestEm14 - how to compute cross sections of EM processes from direct evaluation of the mean-free path. How to plot final state
- TestEm15 - compute and plot final state of Multiple Scattering as an isolated process
- TestEm16 - simulation of synchrotron radiation
- TestEm17 - check the cross sections of high energy muon processes
- TestEm18 - energy lost by a charged particle in a single layer, due to ionization and bremsstrahlung

Check basic quantities	
Total cross sections, mean free paths ...	Em0, Em13, Em14
Stopping power, particle range ...	Em0, Em1, Em5, Em11, Em12
Final state : energy spectra, angular distributions	Em14
Energy loss fluctuations	Em18
Multiple Coulomb scattering	
as an isolated mechanism	Em15
as a result of particle transport	Em5
More global verifications	
Single layer: transmission, absorption, reflexion	Em5
Bragg curve, tallies	Em7
Depth dose distribution	Em11, Em12
Shower shapes, Moliere radius	Em2
Sampling calorimeters, energy flow	Em3
Crystal calorimeters	Em9
Other specialized programs	
High energy muon physics	Em17
Other rare, high energy processes	Em6
Synchrotron radiation	Em16
Transition radiation	Em8
Photo-absorption-ionization model	Em10

Table 9.4. TestEm by theme

9.2.1.3. Error Propagation

- Geant4E - error propagation utility

9.2.1.4. Event Biasing

- Variance Reduction - examples on variance reduction techniques and scoring and application of Reverse MonteCarlo in Geant4 Reverse MonteCarlo

9.2.1.5. Event Generator

- HepMCEx01 - simplified collider detector using HepMC interface and stacking
- HepMCEx02 - connecting primary particles in Geant4 with various event generators using the HepMC interface
- MCTruth - demonstrating a mechanism for Monte Carlo truth handling using HepMC as the event record
- exgps - illustrating the usage of the `G4GeneralParticleSource` utility
- exgps - illustrating the usage of Pythia as Monte Carlo event generator, interfaced with Geant4, and showing how to implement an external decayer

9.2.1.6. Exotic Physics

- Monopole - illustrating how to measure energy deposition in classical magnetic monopole

9.2.1.7. Fields

- BlineTracer - tracing and visualizing magnetic field lines
- field01 - tracking using magnetic field and field-dependent processes
- field02 - tracking using electric field and field-dependent processes
- field03 - tracking in a magnetic field where field associated with selected logical volumes varies
- field04 - definition of overlapping fields either magnetic, electric or both
- field05 - demonstration of "spin-frozen" condition, how to cancel the muon g-2 precession by applying an electric field

9.2.1.8. Geant3 to Geant4

- General ReadMe - converting simple geometries in Geant3.21 to their Geant4 equivalents

9.2.1.9. Geometry

- ReadMe OLAP - debugging tool for overlapping geometries

9.2.1.10. Hadronic

- Hadr00 - example demonstrating the usage of G4PhysListFactory to build physics lists and usage of G4HadronicProcessStore to access the cross sections
- Hadr01 - example based on the application IION developed for simulation of proton or ion beam interaction with a water target. Different aspects of beam target interaction are included

9.2.1.11. Medical Applications

- DICOM - geometry set-up using the Geant4 interface to the DICOM image format
- electronScattering - benchmark on electron scattering
- electronScattering2 - benchmark on electron scattering (second way to implement the same benchmark as the above)
- GammaTherapy - gamma radiation field formation in water phantom by electron beam hitting different targets
- fanoCavity - dose deposition in an ionization chamber by a monoenergetic photon beam
- fanoCavity2 - dose deposition in an ionization chamber by an extended one-dimensional monoenergetic electron source

9.2.1.12. Optical Photons

- General ReadMe
- LXe - optical photons in a liquid xenon scintillator
- WLS - application simulating the propagation of photons inside a Wave Length Shifting (WLS) fiber

9.2.1.13. Parallel Computing

- General ReadMe
- ExDiane - example of a medical application run in a distributed environment using the DIANE framework
- MPI - interface and examples of applications parallelized with different MPI compliant libraries, such as LAM/MPI, MPICH2, OpenMPI, etc.
- ParGeant4 - set of examples (`ParN02` and `ParN04`) derived from `novice` using parallelism at event level with the TopC application

9.2.1.14. Parameterisations

- Gflash - Demonstrates the use of the GFLASH parameterisation library. It uses the GFLASH equations(hep-ex/0001020, Grindhammer & Peters) to parametrise electromagnetic showers in matter

9.2.1.15. Persistency

- General ReadMe
- GDML - examples set illustrating import and export of a detector geometry with GDML, and how to extend the GDML schema
- P01 - storing calorimeter hits using reflection mechanism with Root
- P02 - storing detector description using reflection mechanism with Root
- P03 - illustrating import and export of a detector geometry using ASCII text description and syntax

9.2.1.16. Polarisation

- Pol01 - interaction of polarized beam (e.g. circularly polarized photons) with polarized target

9.2.1.17. Radioactive Decay

- Exrdm - decays of radioactive isotopes as well as induced radioactivity resulted from nuclear interactions

9.2.1.18. Run & Event

- RE01 - information between primary particles and hits and usage of user-information classes
- RE02 - simplified fixed target application for demonstration of primitive scorers
- RE03 - use of UI-command based scoring; showing how to create parallel world(s) for defining scoring mesh(es)

9.2.1.19. Visualization

- Examples of customisation for visualization

9.3. Advanced Examples

9.3.1. Advanced Examples

Geant4 advanced examples illustrate realistic applications of Geant4 in typical experimental environments. Most of them also show the usage of analysis tools (such as histograms, ntuples and plotting), various visualization features and advanced user interface facilities, together with the simulation core.

Note: Maintenance and updates of the code is under the responsibility of the authors. These applications are therefore not subject to regular system testing and no guarantee can be provided.

The advanced examples include:

- **amsEcal** , illustrating simulation in the AMS electro-magnetic calorimeter.
- **brachytherapy** , illustrating a typical medical physics application simulating energy deposit in a Phantom filled with soft tissue.
- **composite_calorimeter** , test-beam simulation of the CMS Hadron calorimeter at LHC.
- **gammaray_telescope** , illustrating an application to typical gamma ray telescopes with a flexible configuration.
- **hadrontherapy** : it is an advanced tool for people interested in Monte Carlo studies related to proton/ion therapy. Hadrontherapy permits the simulation of a typical hadron therapy beam line (with all its elements) and the calculation of fundamentals quantities of interests: 3D dose distributions, fluences, stopping powers, production cross sections for the produced secondary particle, etc.; In the near future new tools will be added: Hadrontherapy will permit the calculation of LET and RBE for both proton and ion beams and it will include the possibility to simulate a typical active scanning proton therapy transport beam line. Please contact the authors for more details on the upcoming features.
- **human_phantom** , implementing an Anthropomorphic Phantom body built importing the description from a GDML representation.
- **medical_linac** , illustrating a typical medical physics application simulating energy deposit in a Phantom filled with water for a typical linac used for intensity modulated radiation therapy. The experimental set-up is very similar to one used in clinical practice.
- **microbeam** , simulates the cellular irradiation beam line installed on the AIFIRA electrostatic accelerator facility located at CENBG, Bordeaux-Gradignan, France.
- **microdosimetry** , simulates the track of a 10 keV Helium+ (positive charge is +e) particle in liquid water using very low energy electromagnetic Geant4 DNA processes.
- **nanobeam** , simulates the beam optics of the "nanobeam line" installed on the AIFIRA electrostatic accelerator facility located at CENBG, Bordeaux-Gradignan, France.
- **purging_magnet** , illustrating an application that simulates electrons traveling through a 3D magnetic field; used in a medical environment for simulating a strong purging magnet in a treatment head.
- **radioprotection** , illustrating an application to evaluate the dose in astronauts, in vehicle concepts and Moon surface habitat configurations, in a defined interplanetary space radiation environment.
- **xray_telescope** , illustrating an application for the study of the radiation background in a typical X-ray telescope.
- **xray_fluorescence** , illustrating the emission of X-ray fluorescence and PIXE.
- **underground_physics** , illustrating an underground detector for dark matter searches.
- **lAr_calorimeter** , simulating the Forward Liquid Argon Calorimeter (FCAL) of the ATLAS Detector at LHC.
- **Rich** , simulating the TestBeam Setup of the Rich detector at the LHCb experiment, testing the performance of the aerogel radiator

For documentation about the analysis tools used in these examples, see Appendix Section 2 of this manual.

Chapter FAQ. Frequentry Asked Questions

FAQ.1. Installation

Q: When I download the source from the web, and unpack the tar file, some files unpack into the top level directory.

A: The problem you describe usually is the result of using "UNIX" tar to unpack the gtar ("GNU-tar") file, or vice versa, or using zip on either the gtar or tar file. Please make certain that you download the correct file for your system, and that you use the correct unpacking tool. Note that for Linux you must download the gtar.gz file.

Q: I cannot find CLHEP files or library and I have it installed in my system.

A: If the standard CLHEP installation procedure has been adopted, the variable `CLHEP_BASE_DIR` should point to the area where `include/` and `lib/` directories for CLHEP headers & library are installed in your system. In case the library file name is different than the one expected (`libCLHEP.a`), you should either create a symbolic link with the expected name, or define the variable `CLHEP_LIB` in your environment which explicitly sets the name of the CLHEP library. If a non-standard CLHEP installation has been adopted, define variables `CLHEP_INCLUDE_DIR`, `CLHEP_LIB_DIR` (and `CLHEP_LIB`) to refer explicitly to the place where headers, library (and library-name) respectively are placed in your system. On Windows systems, the full library file name (with extension) should be specified as `CLHEP_LIB`, while for UNIX-like systems, just the name is required (i.e. `CLHEP` for `libCLHEP.a`).

Q: While installing the Geant4 libraries I get the following message printed:

```
gmake[1]: cernlib: Command not found
```

Has Geant4 been installed properly ? What to do to solve this error ?

A: The message:

```
gmake[1]: cernlib: Command not found
```

shows that you don't have the 'cernlib' command installed in your system; 'cernlib' is a command from the CERN program library (cernlib) returning a list of libraries needed to link a cernlib application. This command is only used in the 'g3tog4' module, however, if you do not make use of the 'g3tog4' tool, it's harmless. The cernlib script (and the needed cernlib libraries) are available from: http://cern.ch/cernlib.

Q: Trying building the Geant4 libraries I see several of these errors appearing and my installation fails:

```
.....G4Exception.d:1: *** missing separator. Stop.
...../G4DalitzDecayChannel.d:1: *** missing separator. Stop.
  :
  :
```

Has Geant4 been installed properly ? What to do to solve this error ?

A: It looks like some file dependencies (.d) are corrupted, possibly due to previous build attempts which failed for some reason. You need to remove each of them. A quick recipe for doing this is to:

- Configure the environment with the installation to be repaired
- Unset the G4WORKDIR environment variable (in case it is eventually set)
- Type:

```
gmake clean dependencies=''
```

from the affected module (i.e. for this case, from $G4INSTALL/source/global/management and $G4INSTALL/source/particles/management) and rebuild. Alternatively, you may use:

```
gmake clean dependencies=''
```

from $G4INSTALL/source and rebuild.

FAQ.2. Run Time Problems

Q: On Linux, I get a segmentation fault as soon as I run one of the official examples.

A: Check that the CLHEP library has been installed and compiled coherently with the same compiler you use for installing Geant4 and for the same version of Linux distribution. For example, a binary object produced with Red-Hat 7.X is not fully compatible with binaries running on RH 9.X or higher, due to different libc used in the two configurations.

Q: I installed Geant4 libraries and built my application, when I try to run it I get:

```
error in loading shared libraries:
libCLHEP.so: cannot open shared object file:
No such file or directory.
```

A: Your installation of CLHEP includes shared libraries. You need to specify the path where libCLHEP.so is installed through your environment variable `LD_LIBRARY_PATH`. For example, in tcsh UNIX shell:

```
setenv LD_LIBRARY_PATH ${LD_LIBRARY_PATH}:$CLHEP_BASE_DIR/lib
```

Q: On my system I get a Floating Point Exception (FPE) since some physics processes sometimes return `DBL_MAX` as interaction length and this number is afterwards multiplied by a number greater than 1.

A: Geant4 coding conventions and installation setup explicitly follow the ANSI/IEEE-754 Standard for the initialization of floating-point arithmetic hardware and portability. The Standard foresees floating-point arithmetic to be nonstop and underflows to be gradual. On DEC platforms, for example, the ANSI/IEEE-754 Standard compliance needs to be explicitly set (since deactivated by default); in this case we use infact the option "-ieee" on the DEC/cxx native C++ compiler to achieve this. You should check if your compiler provides compilation options for activating Standard initialization of FP arithmetic (it may be platform specific).

FAQ.3. Geometry

Q: I have a generic point and I would like to know in which physical volume I'm located in my detector geometry.

A: The best way of doing this is by invoking the G4Navigator. First get a pointer of the navigator through the G4TransportationManager, and then locate the point. i.e.

```
#include "G4TransportationManager.hh"
#include "G4Navigator.hh"
G4ThreeVector myPoint = ....;
G4Navigator* theNavigator = G4TransportationManager::GetTransportationManager()
                            ->GetNavigatorForTracking();
G4VPhysicalVolume* myVolume = theNavigator->LocateGlobalPointAndSetup(myPoint);
```

Note

by using the navigator for tracking as shown above, the actual particle gets also -relocated- in the specified position. Therefore, if this information is needed during tracking time, in order to avoid affecting tracking, you should either use an alternative G4Navigator object (which you then assign to your world-volume), or you access the information through the track or touchable as specified in the FAQ for tracking and steps.

Q: How can I access the daughter volumes of a specific physical volume?

A: Through the associated logical volume.

```
G4VPhysicalVolume* myPVolume = ....;
G4LogicalVolume* myLVolume = myPVolume->GetLogicalVolume();
for (G4int i=0; iGetNoDaughters(); i++)
  myPVolume = myLVolume->GetDaughter(i);
```

Q: How can I identify the exact copy-number of a specific physical volume in my mass geometry? I tried with GetCopyNo() from my physical volume pointer, but it doesn't seem to work!

A: The correct way to identify -uniquely- a physical volume in your mass geometry is by using the touchables (see also section 4.1.5 of the User's Guide for Application Developers), as follows:

```
G4Step* aStep = ..;
G4StepPoint* preStepPoint = aStep->GetPreStepPoint();
G4TouchableHandle theTouchable = preStepPoint->GetTouchableHandle();
G4int copyNo = theTouchable->GetCopyNumber();
G4int motherCopyNo = theTouchable->GetCopyNumber(1);
```

where `Copy` here stays for any duplicated instance of a physical volume, either if it is a `G4PVPlacement` (multiple placements of the same logical volume) or a `G4PVReplica/G4PVParameterised`. The method `GetCopyNo()` is meant to return only the serial number of placements not duplicated in the geometry tree.

Q: How can I determine the exact position in global coordinates in my mass geometry during tracking and how can I convert it to coordinates local to the current volume ?

A: You need again to do it through the touchables (see also section 4.1.5 of the User's Guide for Application Developers), as follows:

```
G4Step* aStep = ..;
G4StepPoint* preStepPoint = aStep->GetPreStepPoint();
G4TouchableHandle theTouchable = preStepPoint->GetTouchableHandle();
G4ThreeVector worldPosition = preStepPoint->GetPosition();
G4ThreeVector localPosition = theTouchable->GetHistory()->
                              GetTopTransform().TransformPoint(worldPosition);
```

where `worldPosition` here stays for the position related to the world volume, while `localPosition` refers to the coordinates local to the volume where the particle is currently placed.

FAQ.4. Tracks and steps

Q: How can I access the track information through the step object and what information am I allowed to access ?

A: A `G4Step` object consists of two points:

```
G4StepPoint* point1 = step->GetPreStepPoint();
G4StepPoint* point2 = step->GetPostStepPoint();
```

To get their positions in the global coordinate system:

```
G4ThreeVector pos1 = point1->GetPosition();
G4ThreeVector pos2 = point2->GetPosition();
```

Hereafter we call current volume the volume where the step has just gone through. Geometrical informations are available from `preStepPoint`. `G4VTouchable` and its derivates keep these geometrical informations. We retrieve a touchable by creating a handle for it:

```
G4TouchableHandle touch1 = point1->GetTouchableHandle();
```

To get the current volume:

```
 G4VPhysicalVolume* volume = touch1->GetVolume();
```

To get its name:

```
G4String name = volume->GetName();
```

To get the physical volume copy number:

```
G4int copyNumber = touch1->GetCopyNumber();
```

To get logical volume:

```
G4LogicalVolume* lVolume = volume->GetLogicalVolume();
```

To get the associated material: the following statements are equivalent:

```
G4Material* material = point1  ->GetMaterial();
G4Material* material = lVolume ->GetMaterial();
```

To get the geometrical region:

```
G4Region* region = lVolume->GetRegion();
```

To get its mother volume:

```
G4VPhysicalVolume* mother = touch1->GetVolume(depth=1);
grandMother: depth=2 ...etc...
```

To get the copy number of the mother volume:

```
G4int copyNumber = touch1->GetCopyNumber(depth=1);
grandMother: depth=2 ...etc...
```

To get the process which has limited the current step:

```
G4VProcess* aProcess = point2->GetProcessDefinedStep();
```

To check that the particle has just entered in the current volume (i.e. it is at the first step in the volume; the `preStepPoint` is at the boundary):

```
if (point1->GetStepStatus() == fGeomBoundary)
```

To check that the particle is leaving the current volume (i.e. it is at the last step in the volume; the `postStepPoint` is at the boundary):

```
if (point2->GetStepStatus() == fGeomBoundary)
```

In the above situation, to get touchable of the next volume:

```
G4TouchableHandle touch2 = point2->GetTouchableHandle();
```

From `touch2`, all informations on the next volume can be retrieved as above.

Physics quantities are available from the step (`G4Step`) or from the track (`G4Track`).

To get the energy deposition, step length, displacement and time of flight spent by the current step:

```
G4double eDeposit      = step->GetTotalEnergyDeposit();
G4double sLength       = step->GetStepLength();
G4ThreeVector displace = step->GetDeltaPosition();
G4double tof           = step->GetDeltaTime();
```

To get momentum, kinetic energy and global time (time since the beginning of the event) of the track after the completion of the current step:

```
G4Track* track         = step->GetTrack();
G4ThreeVector momentum = track->GetMomentum();
G4double kinEnergy     = track->GetKineticEnergy();
G4double globalTime    = track->GetGlobalTime();
...etc...
```

Remark

To transform a position from the global coordinate system to the local system of the current volume, use the `preStepPoint` transformation, as described in the geometry section above.

FAQ.5. Physics and cuts

Q: How do production cuts (in range) work in Geant4 ? Are they also used in tracking ? If a particle has an energy lower than the converted cut in energy for the given material and the distance to the next boundary is smaller than the cut in range, is the particle killed ?

A: Geant4 does **NOT** have a "tracking cut". The toolkit's default behaviour is to track particles down to zero range (i.e. zero energy). Of course, it is possible for the user to create and register a process that kills particles below a certain energy or range; this is however **NOT** provided by default in Geant4. So there's **NO** "tracking cut". For example, suppose a particle that is nearing zero energy will at some point be proposed by its Ionisation process to undergo one final step, from its current energy down to zero energy. This is still only a proposal. If during this step the particle crosses a boundary, then the transportation will limit the step at a length smaller than the Ionisation -- so the particle will still see and cross the relevant boundary, and another step will occur on the other side of that boundary. In summary the "production threshold" range and its equivalent in energy are not utilised as a "tracking cut". A particle is not abandoned by Geant4 below a certain range/energy unless the user registers a process to do this by him/her-self.

FAQ.6. Visualization

Q: I have set G4VIS... environmental variables but visualization does not appear to be enabled.

A: This might be because you set the environment variables *after* already compiling. The environment variables control C-pre-processor macros of the same name and therefore influence what code gets compiled. It is suggested to proceed with the following manual procedure to correct the current installation:

- Configure the environment according to the installation making sure to -unset- the `G4WORKDIR` environment variable, if set.
- Verify and eventually set the environment variables of the visualization module [name] concerned (setenv or export both `G4VIS_BUILD_[name]_DRIVER` and `G4VIS_USE_[name]` variables according to the UNIX shell used), and then proceed as follows:

```
cd $G4INSTALL/source/visualization
gmake clean
gmake
cd $G4INSTALL/source/interfaces
gmake clean
gmake
cd $G4INSTALL/source
gmake libmap
setenv G4WORKDIR [your working directory]   (or export)
cd [your application directory]
gmake clean
gmake
```

Q: While visualizing my geometry setup I often see the following error message printed out:

```
BooleanProcessor: boolean operation failed .
```

A: There is a known limitation for the visualization of Boolean solids in the so-called BooleanProcessor which is used to make polyhedra for visualisation. It does not affect the tracking which is done through such solids. So the error message you see does not affect the simulation in any way. The workaround is to move one of the affected solids by a small distance in order to avoid shared surfaces.

FAQ.7. User Support Policy

Q: If I need to discuss technical matters specific to my simulation application or ask for first-aid help, who can I contact?

A: Every institute and experiment participating in Geant4 has a G4 Technical Steering Board (TSB) representative who may be contacted for help with problems relating to simulations. Please contact the TSB representative closest to your project or to your laboratory. To find out who your TSB representative is go to G4 Technical Board. You may also post your question in the Geant4 HyperNews Forum.

Q: If I find a bug or other problem with the code, who should be informed?

A: A WWW interface, available at Problem tracking system, will forward the bug report to the person responsible for the affected Geant4 domain. The Geant4 web makes available a database of open incident reports, tagging the ones already fixed and showing their status. An acknowledgement of the bug report will be sent.

Q: If I propose a fix, who is responsible for approving it?

A: The responsible person is the working group coordinator of the domain in which the fix is to be applied. This person is usually also a TSB member. If the fix affects more than one domain, the matter will be addressed by the TSB.

Q: To whom should I send a proposal for an improvement in Geant4 functionality?

A: Any new requirement should be submitted via the automatic web system. It will be discussed at the Geant4 TSB. You may also ask your TSB representative to forward your requirement to the TSB. A new requirement will trigger a cycle of analysis, design, implementation, testing and documentation, which may involve different working groups. Any new software or enhancement which will become a part of Geant4 must be agreed upon by the TSB, which is charged with ensuring the consistency of the entire toolkit.

Q: Is there a regular user meeting which I should attend?

A: There is only one Geant4 workshop per year. However, many experiments and institutes in the Geant4 collaboration organize their own regular and/or special Geant4 user workshops.

Q: Where can I find solutions to particular problems as well as general user support?

A: Solutions and tips for solving practical problems can be found on the current FAQ page. General and specific user support information is available at the User Support page.

Appendix . Appendix

1. Tips for Program Compilation

This section is dedicated to illustrate and justify some of the options used and fixed by default in the compilation of the Geant4 toolkit. It is also meant to be a simple guide for the user/installer to avoid or overcome problems which may occur on some compilers. Solutions proposed here are based on the experience gained while porting the Geant4 code to different architectures/compilers and are specific to the OS's and compiler's version valid at the current time of writing of this manual.

It's well known that each compiler adopts its own internal techniques to produce the object code, which in the end might be more or less perfomant and more or less optimised, depending on several factors also related to the system architecture which it applies to.

After the installation of the libraries, we strongly suggest to always distinguish between the installation directory (identified by $G4INSTALL) and the working directory (identified by $G4WORKDIR), in order not to alter the installation area.

1.1. Unix/Linux - g++

OS: Linux

Compiler: GNU/gcc

Strict ISO/ANSI compilation is forced (`-ansi -pedantic` compiler flags), also code is compiled with high verbosity diagnostics (`-Wall` flag). The default optimisation level is `-O2`. The flag `G4OPTDEBUG`, if set in the environment, allows for optimised build of the libraries but including debug symbols (`-O -g` compilation option).

Note

Additional compilation options (`-march=XXX -mfpmath=sseYYY`) to adopt chip specific floating-point operations on the SSE unit, can be activated by adapting the `XXX, YYY` options and uncommenting the relevant part in the `Linux-g++.gmk` configuration script. By doing so, it has been verified a greater stability of results, making possible reproducibility of exact outputs between debug, non-optimised and optimised runs. A little performance improvement (in the order of 2%) can also be achieved in some cases. To be considered that binaries built using these chip-specific options will likely NOT be portable cross platforms; generated applications will only run on the specific chip-based architectures.

1.2. Windows - MS Visual C++

OS: MS/Windows

Compiler: MS-VC++

Since version .NET 7.0 of the compiler, ISO/ANSI compliance is required.

See Section 3.1 of the Installation Guide for more detailed information. See also Section 6.1 for more tips.

1.3. MacOS-X - g++

OS: MacOS/Darwin

Compiler: GNU/gcc

The setup adopted for the `g++` compiler on MacOS resembles in most parts the one for Linux systems.

The default optimisation level in this case is `-O2`.

Dynamic libraries (`.dylib`) are supported as well; once built, in order to run the generated application, the user must specify the absolute path in the system where they're installed with the `DYLD_LIBRARY_PATH` system variable.

2. Histogramming

Geant4 is independent of any histogramming package. The Geant4 toolkit has no drivers for histogramming, and no drivers are needed in Geant4 to use a histogramming package. The code for generating histograms on some of the distributed examples should be compliant with the AIDA abstract interfaces for Data Analysis.

Consequently, you may use your favourite package together with the Geant4 toolkit.

2.1. JAS

Please refer to the JAS documentation on histogramming for using the JAVA Analysis Studio tool.

2.2. iAida

Please refer to the iAIDA (an implementation of AIDA in C++) documentation : tool for generating histograms with AIDA to HBook, Root and AIDA-native compressed XML format.

2.3. Open Scientist Lab

Please refer to the Open Scientist Lab documentation on histogramming for using the Lab Analysis plug-in for the OnX package.

2.4. rAIDA

Please refer to the rAIDA documentation (a Root implementation of AIDA): Root plugin for generating histograms with AIDA.

2.5. Examples

Examples in Geant4 showing how to use AIDA compliant tools for histogramming are available in the code distribution in the following directories:

- `geant4/examples/extended/analysis`,
- `geant4/examples/extended/electromagnetic`
- `geant4/examples/advanced`

3. CLHEP Foundation Library

CLHEP is a set of Class Libraries containing many basic classes for use in High Energy Physics.

Both a CLHEP Reference Guide and a User Guide are available.

Origin and current situation of CLHEP

CLHEP started in 1992 as a library for fundamental classes mostly needed for, and in fact derived from, the MC event generator MC++ written in C++. Since then various authors added classes to this package, including several contributions made by developers in the Geant4 Collaboration.

Geant4 and CLHEP

The Geant4 project contributed to the development of CLHEP. The random number package, physics units and constants, and some of the numeric and geometry classes had their origins in Geant4.

Geant4 also benefits from the development of CLHEP. In addition to the already mentioned classes for random numbers and numerics, we use the classes for points, vectors, and planes and their transformations in 3D space,

and lorentz vectors and their transformations. Although these classes have Geant4 names like G4ThreeVector, these are just typedefs to the CLHEP classes.

4. C++ Standard Template Library

Overview

The Standard Template Library (STL) is a general-purpose library of generic algorithms and data structures. It is part of the C++ Standard Library. Nowadays, most compiler vendors include a version on STL in their products, and there are commercial implementations available as well.

Good books on STL are:

- Nicolai M. Josuttis: The C++ Standard Library. A Tutorial and Reference [Josuttis1999]
- David R. Musser, Atul Saini: STL Tutorial and Reference Guide / C++ Programming with the Standard Template Library [Musser1996]
- Scott Meyers: Effective STL [Meyers2001]

Resources available online include the reference of the SGI implementation:

- SGI STL homepage , this is the basis of the native egcs STL implementation.

STL in Geant4

Since release 0.1, Geant4 supports STL, the Standard Template Library. From release 1.0 of Geant4, STL is required.

Native implementations of STL are foreseen on all supported platforms.

5. Makefiles and Environment Variables

This section describes how the GNUmake infrastructure is implemented in Geant4 and provides a quick reference guide for the user/installer about the most important environment variables defined.

5.1. The GNUmake system in Geant4

As described in Section 2.1 of the Installation Guide, the GNUmake process in Geant4 is mainly controlled by the following GNUmake script files (`*.gmk` scripts are placed in `$G4INSTALL/config`):

- `architecture.gmk`: defining all the architecture specific settings and paths. System settings are stored in `$G4INSTALL/config/sys` in separate files.
- `common.gmk`: defining all general GNUmake rules for building objects and libraries.
- `globlib.gmk`: defining all general GNUmake rules for building compound libraries.
- `binmake.gmk`: defining the general GNUmake rules for building executables.
- `GNUmake` scripts: placed inside each directory in the G4 distribution and defining directives specific to build a library (or a set of sub-libraries) or and executable.

To build a single library (or a set of sub-libraries) or an executable, you must explicitly change your current directory to the one you're interested in and invoke the "`make`" command from there ("`make global`" for building a compound library). Here is a list of the basic commands or GNUmake "targets" one can invoke to build libraries and/or executables:

- `make`

  starts the compilation process for building a kernel library or a library associated with an example. Kernel libraries are built with maximum granularity, i.e. if a category is a compound, this command will build all the related sub-libraries, **not** the compound one. The top level `GNUmakefile` in `$G4INSTALL/source` will also build in this case a dependency map `libname.map` of each library to establish the linking order automatically at the `bin` step. The map will be placed in `$G4LIB/$G4SYSTEM`.
- `make global`

starts the compilation process to build a single compound kernel library per category. If issued after "make", both 'granular' and 'compound' libraries will be available (NOTE: this will consistently increase the disk space required. Compound libraries will then be selected by default at link time, unless G4LIB_USE_GRANULAR is specified).

- `make bin` or `make` (only for examples/)

  starts the compilation process to build an executable. This command will build implicitly the library associated with the example and link the final application. It assumes **all** kernel libraries are already generated and placed in the correct `$G4INSTALL` path defined for them.

  The linking order is controlled automatically in case libraries have been built with maximum granularity, and the link list is generated on the fly.
- `make dll`

  On Windows systems this will start the compilation process to build single compound kernel library per category and generate Dynamic Link Libraries (DLLs). Once the libraries are generated, the process will imply also the deletion of all temporary files generated during the compilation.

`lib/ bin/` and `tmp/` directories

The `$G4INSTALL` environment variable specifies where the installation of the Geant4 toolkit should take place, therefore kernel libraries will be placed in `$G4INSTALL/lib`. The `$G4WORKDIR` environment variable is set by the user and specifies the path to the user working directory; temporary files (object-files and data products of the installation process of Geant4) will be placed in `$G4WORKDIR/tmp`, according to the system architecture used. Binaries will be placed in `$G4WORKDIR/bin`, according to the system architecture used. The path to `$G4WORKDIR/bin/$G4SYSTEM` should be added to `$PATH` in the user environment.

5.2. Environment variables

Here is a list of the most important environment variables defined within the Geant4 `GNUmake` infrastructure, with a short explanation of their use.

We recommend that those environment variables listed here and marked with (*) NOT be overriden or set (explicitly or by accident). They are already set and used internally in the default setup !

System configuration

$CLHEP_BASE_DIR
: Specifies the path where the CLHEP package is installed in your system.

$G4SYSTEM
: Defines the architecture and compiler currently used.

  NOTE: This variable is set automatically if the `Configure` script is adopted for the installation. This will result in the proper settings also for configuring the environment with the generated shell scripts `env.[c]sh`.

Installation paths

$G4INSTALL
: Defines the path where the Geant4 toolkit is located. It should be set by the system installer. By default, it sets to `$HOME/geant4`, assuming the Geant4 distribution is placed in `$HOME`.

$G4BASE **(*)**
: Defines the path to the source code. Internally used to define `$CPPFLAGS` and `$LDFLAGS` for -I and -L directives. It has to be set to `$G4INSTALL/src`.

$G4WORKDIR
: Defines the path for the user's workdir for Geant4. It is set by default to `$HOME/geant4`, assuming the user's working directory for Geant4 is placed in `$HOME`.

$G4INCLUDE
Defines the path where source header files may be mirrored at installation by issuing `gmake includes` (default is set to `$G4INSTALL/include`)

$G4BIN, $G4BINDIR **(*)**
Used by the system to specify the place where to store executables. By default they're set to `$G4WORKDIR/bin` and `$G4BIN/$G4SYSTEM` respectively. The path to `$G4WORKDIR/bin/$G4SYSTEM` should be added to `$PATH` in the user environment. `$G4BIN` can be overridden.

$G4TMP, $G4TMPDIR **(*)**
Used by the system to specify the place where to store temporary files products of the compilation/build of a user application or test. By default they're set to `$G4WORKDIR/tmp` and `$G4TMP/$G4SYSTEM` respectively. `$G4TMP` can be overridden.

$G4LIB, $G4LIBDIR **(*)**
Used by the system to specify the place where to install libraries. By default they're set to `$G4INSTALL/lib` and `$G4LIB/$G4SYSTEM` respectively. `$G4LIB` can be overridden.

Build specific

$G4TARGET
Specifies the target (name of the source file defining the main()) of the application/example to be built. This variable is set automatically for the examples and tests placed in `$G4INSTALL/examples`.

$G4DEBUG
Specifies to compile the code (libraries or examples) including symbolic information in the object code for debugging. The size of the generated object code can increase considerably. By default, code is compiled in optimised mode (`$G4OPTIMISE` set).

$G4OPTDEBUG
Only available for the `g++` compiler, specifies to compile the code (libraries or examples) in optimised mode, but including symbolic information in the object code for debugging.

$G4NO_OPTIMISE
Specifies to compile the code (libraries or examples) without compiler optimisation.

$G4PROFILE
On `Linux` systems with the `g++` compiler, it allows to build libraries with profiling setup for monitoring with the `gprof` tool.

$G4_NO_VERBOSE
Geant4 code is compiled by default in high verbosity mode (`$G4VERBOSE` flag set). For better performance, verbosity code can be left out by defining `$G4_NO_VERBOSE`.

$G4LIB_BUILD_SHARED
Flag specifying if to build kernel libraries as shared libraries (libraries will be then used by default). If not set, static archive libraries are built by default.

$G4LIB_BUILD_STATIC
Flag specifying if to build kernel libraries as static archive libraries in addition to shared libraries (in case `$G4LIB_BUILD_SHARED` is set as well).

$G4LIB_BUILD_DLL **(*)**
Internal flag for specifying to build DLL kernel libraries for Windows systems. The flag is automatically set when requested to build DLLs.

$G4LIB_USE_DLL
For Windows systems only. Flag to specify to build an application using the installed DLL kernel libraries for Windows systems. It is required to have this flag set in the environment in order to successfully build an application if the DLL libraries have been installed.

$G4LIB_USE_GRANULAR
To force usage of "granular" libraries against "compound" libraries at link time in case both have been installed. The Geant4 building system chooses "compound" libraries by default, if installed.

UI specific

The most relevant flags for User Interface drivers are just listed here. A more detailed description is given also in section 2. of this User's Guide.

G4UI_USE_TERMINAL
Specifies to use dumb terminal interface in the application to be built (default).

G4UI_USE_TCSH
Specifies to use the tcsh-shell like interface in the application to be built.

G4UI_BUILD_XM_SESSION, G4UI_BUILD_XAW_SESSION
Specifies to include in kernel library the *XM* or *XAW* Motif-based user interfaces.

G4UI_USE_XM, G4UI_USE_XAW
Specifies to use the *XM* or *XAW* interfaces in the application to be built.

G4UI_BUILD_WIN32_SESSION
Specifies to include in kernel library the WIN32 terminal interface for Windows systems.

G4UI_USE_WIN32
Specifies to use the WIN32 interfaces in the application to be built on Windows systems.

G4UI_BUILD_QT_SESSION
Specifies to include in kernel library the Qt terminal interface. `$QTHOME` should specify the path where Qt libraries and headers are installed

G4UI_USE_QT
Specifies to use the Qt interfaces in the application to be built.

G4UI_NONE
If set, no UI sessions nor any UI libraries are built. This can be useful when running a pure batch job or in a user framework having its own UI system.

Visualization specific

The most relevant flags for visualization graphics drivers are just listed here. A description of these variables is given also in section 2. of this User's Guide.

$G4VIS_BUILD_OPENGLX_DRIVER
Specifies to build kernel library for visualization including the OpenGL driver with X11 extension. It requires `$OGLHOME` set (path to OpenGL installation).

$G4VIS_USE_OPENGLX
Specifies to use OpenGL graphics with X11 extension in the application to be built.

$G4VIS_BUILD_OPENGLXM_DRIVER
Specifies to build kernel library for visualization including the OpenGL driver with XM extension. It requires `$OGLHOME` set (path to OpenGL installation).

$G4VIS_USE_OPENGLXM
Specifies to use OpenGL graphics with XM extension in the application to be built.

G4VIS_BUILD_OPENGLQT_DRIVER
Specifies to build kernel library for visualization including the OpenGL driver with Qt extension. It requires `$QTHOME` set to specify the path where Qt libraries and headers are installed.

G4VIS_USE_OPENGLQT
Specifies to use OpenGL graphics with Qt extension in the application to be built.

$G4VIS_BUILD_OI_DRIVER
Specifies to build kernel library for visualization including the OpenInventor driver. It requires `$OIHOME` set (paths to the `OpenInventor` installation).

$G4VIS_USE_OI
Specifies to use OpenInventor graphics in the application to be built.

$G4VIS_BUILD_OIX_DRIVER
Specifies to build the driver for the free X11 version of OpenInventor.

$G4VIS_USE_OIX
Specifies to use the free X11 version of OpenInventor.

$G4VIS_BUILD_RAYTRACERX_DRIVER
Specifies to build kernel library for visualization including the Ray-Tracer driver with X11 extension. It requires `X11` installed in the system.

$G4VIS_USE_RAYTRACERX
Specifies to use the X11 version of the Ray-Tracer driver.

$G4VIS_BUILD_OIWIN32_DRIVER
Specifies to build the driver for the free X11 version of OpenInventor on Windows systems.

$G4VIS_USE_OIWIN32
Specifies to use the free X11 version of OpenInventor on Windows systems.

$G4VIS_BUILD_DAWN_DRIVER
Specifies to build kernel library for visualization including the driver for DAWN.

$G4VIS_USE_DAWN
Specifies to use DAWN as a possible graphics renderer in the application to be built.

$G4DAWN_HOST_NAME
To specify the hostname for use with the DAWN-network driver.

$G4VIS_NONE
If specified, no visualization drivers will be built or used.

Hadronic physics specific

$G4NEUTRONHP_USE_ONLY_PHOTONEVAPORATION
When using high precision neutron code, user may choose to force the use of Photon Evaporation model instead of using the neutron capture final state data.

$G4NEUTRONHP_SKIP_MISSING_ISOTOPES
User can force high precison neutron code to use only exact isotope data files instead of allowing nearby isotope files to be used. If the exact file is not available, the cross section will be set to zero and a warning message will be printed.

$G4NEUTRONHP_NEGLECT_DOPPLER
Sets neglecting doppler broadening mode for boosting performance.

`GDML`, `zlib` and `g3tog4` modules

$G4LIB_BUILD_GDML
If set, triggers compilation of a plugin module `gdml` for allowing import/export of detector description setups (geometrical volumes, solids, materials, etc.). By default, the flag is not set; if set, the path to the installation of XercesC package must be specified through the variable `$XERCESCROOT`.

$G4LIB_USE_GDML
Specifies to use the `gdml` module. The flag is automatically set if `$G4LIB_BUILD_GDML` is set in the environment.

$G4LIB_BUILD_ZLIB
If set, triggers compilation of a specific `zlib` module for the compression of output files (mainly in use currently for the HepRep graphics driver). By default, the flag is not set and the built-in system library for compression is adopted instead. Setting this flag will also implicitely set the flag below. On Windows systems, if OpenGL or OpenInventor visualization drivers are built, this module is automatically built.

$G4LIB_USE_ZLIB
Specifies to use the `zlib` module, either system built-in or Geant4 specific.

$G4LIB_BUILD_G3TOG4
If set, triggers compilation of the `g3tog4` module for conversions of simple legacy geometries descriptions to Geant4. By default, the flag is not set and the module's library is not built. Setting this flag will also implicitely set the flag below.

$G4LIB_USE_G3TOG4
Specifies to use the `g3tog4` module, assuming the related library has been already installed.

Analysis specific

$G4ANALYSIS_USE
Specifies to activate the appropriate environment for analysis, if an application includes code for histogramming based on *AIDA*. Additional setup variables are required (`$G4ANALYSIS_AIDA_CONFIG_CFLAGS`, `$G4ANALYSIS_AIDA_CONFIG_LIBS`) to define config options for AIDA ("`aida-config --cflags`" and "`aida-config --libs`"). See installation instructions of the specific analysis tools for details.

Directory paths to Physics Data

$G4NEUTRONHPDATA
Path to external data set for Neutron Scattering processes.

$G4LEDATA
Path to external data set for low energy electromagnetic processes.

$G4LEVELGAMMADATA
Path to the data set for Photon Evaporation.

$G4RADIOACTIVEDATA
Path to the data set for Radiative Decay processes.

$G4ABLADATA
Path to nuclear shell effects data set for INCL/ABLA hadronic model.

$G4REALSURFACEDATA
Path to the data set for measured optical surface reflectance for precise optical physics.

$G4REALSURFACEDATA
Path to the Look-Up-Tables for the LUT model of optical photon boundary reflection.

5.3. Linking External Libraries with Geant4

The Geant4 GNUmake infrastructure allows to extend the link list of libraries with external (or user defined) packages which may be required for some user's applications to generate the final executable.

5.3.1. Adding external libraries which do *not* use Geant4

In the `GNUmakefile` of your application, before including `binmake.gmk`, specify the extra library in `EXTRALIBS` either using the `-L...-l...` syntax or by specifying the full pathname, e.g.:

```
EXTRALIBS := -L<your-path>/lib -l<myExtraLib>
```

or

```
EXTRALIBS := <your-path>/lib/lib<myExtraLib>.a
```

You may also specify `EXTRA_LINK_DEPENDENCIES`, which is added to the dependency of the target executable, and you may also specify a rule for making it, e.g.:

```
EXTRA_LINK_DEPENDENCIES := <your-path>/lib/lib<myExtraLib>.a

<your-path>/lib/lib<myExtraLib>.a:
      cd <your-path>/lib; $(MAKE)
```

Note that you almost certainly need to augment `CPPFLAGS` for the header files of the external library, e.g.:

```
CPPFLAGS+=-I<your-path>/include
```

See Example 85.

Example 85. An example of a customised GNUmakefile for an application or example using an external module not bound to Geant4.

```
# --------------------------------------------------------------------
# GNUmakefile for the application "sim" depending on module "Xplotter"
# --------------------------------------------------------------------

name := sim
G4TARGET := $(name)
G4EXLIB := true

CPPFLAGS  += -I$(HOME)/Xplotter/include
EXTRALIBS += -L$(HOME)/Xplotter/lib -lXplotter
EXTRA_LINK_DEPENDENCIES := $(HOME)/Xplotter/lib/libXplotter.a

.PHONY: all

all: lib bin

include $(G4INSTALL)/config/binmake.gmk

$(HOME)/Xplotter/lib/libXplotter.a:
       cd $(HOME)/Xplotter; $(MAKE)
```

5.3.2. Adding external libraries which use Geant4

In addition to the above, specify, in `EXTRALIBSSOURCEDIRS`, a list of directories containing source files in its `src/` subdirectory. Thus, your `GNUmakefile` might contain:

```
EXTRALIBS += $(G4WORKDIR)/tmp/$(G4SYSTEM)/<myApp>/lib<myApp>.a \
             -L<your-path>/lib -l<myExtraLib>
EXTRALIBSSOURCEDIRS += <your-path>/<myApp> <your-path>/<MyExtraModule>
EXTRA_LINK_DEPENDENCIES := $(G4WORKDIR)/tmp/$(G4SYSTEM)/<myApp>/lib<myApp>.a

MYSOURCES := $(wildcard <your-path>/<myApp>/src/*cc)
$(G4WORKDIR)/tmp/$(G4SYSTEM)/<myApp>/lib<myApp>.a: $(MYSOURCES)
      cd <your-path>/<myApp>; $(MAKE)
```

See Example 86.

Example 86. An example of a customised GNUmakefile for an application or example using external modules bound to Geant4.

```
# --------------------------------------------------------------
# GNUmakefile for the application "phys" depending on module "reco"
# --------------------------------------------------------------

name := phys
G4TARGET := $(name)
G4EXLIB := true

EXTRALIBS += $(G4WORKDIR)/tmp/$(G4SYSTEM)/$(name)/libphys.a \
             -L$(HOME)/reco/lib -lreco
EXTRALIBSSOURCEDIRS += $(HOME)/phys $(HOME)/reco
EXTRA_LINK_DEPENDENCIES := $(G4WORKDIR)/tmp/$(G4SYSTEM)/$(name)/libphys.a

.PHONY: all
all: lib bin

include $(G4INSTALL)/config/binmake.gmk

MYSOURCES := $(wildcard $(HOME)/phys/src/*cc)
$(G4WORKDIR)/tmp/$(G4SYSTEM)/$(name)/libphys.a: $(MYSOURCES)
        cd $(HOME)/phys; $(MAKE)
```

6. Step-by-Step Installation Guides

You can find below some useful pages collecting instructions on how to install Geant4 in a detailed step-by-step tutorial:

- Step by step Installation Guides.

6.1. Building on MS Visual C++

Geant4 can be compiled with the C++ compiler of MS Visual Studio C++ and the Cygwin toolset. Detailed instructions are given in the Installation manual. As the build system relies on `make` and other Unix tools using only the compiler of MS Visual Studio, the section on

Section 5 Makefile and environment variables applies also for building with MS Visual C++.

We do not support compilation directly under MS Visual Studio, i.e. we do not provide workspace files (`.dsw`) or project files (`.dsp`).

However the executables created are debuggable using the debugger of MS Visual Studio. You may have to help the debugger finding the path to source files the first time you debug a given executable.

Listed below are some useful pages with instructions on how to start with the installation of CygWin, and also tips for creating a project under Visual Studio:

- Getting started with Cygwin.
- Cygwin Installation Notes.
- Building a MSVC++ Visual Studio 2005 Geant4 project (setup no longer supported).

7. Development and debug tools

7.1. UNIX

Although not in the scope of this user manual, in this appendix section we provide a set of references to rather known and established development tools and environments we think are useful for code development in C++ in general. It's a rather limited list, far from being complete of course.

- The KDevelop environment on Linux systems.
- The GNU Data Display Debugger (DDD).
- Valgrind , a system for debugging and profiling Linux programs.

- Microsoft Visual Studio development environment.
- Parasoft Insure++ run-time debugger and memory checker
- Parasoft C++ Test source code analyzer.
- Enterprise Architect UML Visual Modeling tool.
- Borland Together Visual Modeling for Software Architecture Design tool.

8. Python Interface

Python is a popular scripting language with an interactive interpreter. Geant4Py, a Geant4-Python bridge, provides a bridge for Geant4 classes. This enables to directly access Geant4 classes from Python scripting. User applications can be easily configured with many Python third-party modules, such as PyROOT, on the Python software bus.

Geant4Py is located in the directory `environments/g4py/`.

8.1. Installation

8.1.1. Software Requirements

Geant4Py requires Boost-C++ external library, which helps Python binding of C++ codes. A Precompiled package is available for many Linux distributions (SL, SuSE, Ubuntu, etc) and Mac OSX.

Geant4 libraries can be built as "static" and "granular", where library components (variables, functions, ...) used in the application are linked statically and shipped with the application. On the other hands, in dynamic binding, the library components are not included in the application, and their binding is carried out at run time. The modular approach of Python is based on dynamic binding mechanism, so you have Geant4 shared libraries are required instead.

For generic information about building Geant4 libraries, please refer to the Installation Guide.

Here are some tips for manually building "global" and "shared" libraries from an already existing "static + granular" installation. After setting additional environment variables like:

Environment Variable	Description	Value (example)
G4LIB	Path where the Geant4 libraries are installed	$G4INSTALL/slib
G4TMP	Path where temporary files are placed	$G4INSTALL/tmp-slib
G4LIB_BUILD_SHARED	Flag for building shared libraries	1

Table 11. Additional environment variables for building global and shared library

execute the following:

```
# cd $G4INSTALL/source
# make
# make global
```

In addition, it is required that all header files are installed in a single directory.

```
# cd $G4INSTALL/source
# make includes
```

This will collect all relevant header files in `$G4INSTALL/include` (or `$G4INCLUDE`).

There are additional tools for helping building a Geant4 library in the directory `g4py/tools/`.

8.1.2. Building Geant4Py module

Geant4Py provides a configure scrtipt for building modules.

```
# ./configure --help
`configure' configures Geant4Py to adapt to many kinds of systems.
```

```
Usage:  ./configure SYSTEM [OPTION]... [VAR=VALUE]...

SYSTEM: System type (see Supported Arhitectures)

Options:
  -h, --help               Display this help and exit

Installation directories:
  --prefix=PREFIX          Installation prefix  [./]
  --libdir=DIR             Python modules dir [PREFIX/lib]

Fine tuning of the library path:
  --with-g4-incdir=DIR     Geant4 header dir [$G4INCLUDE]
  --with-g4-libdir=DIR     Geant4 library dir [$G4LIB/$G4SYSTEM]
  --with-clhep-incdir=DIR  CLHEP header dir [$CLHEP_INCLUDE_DIR]
  --with-clhep-libdir=DIR  CLHEP library dir [$CLHEP_LIB_DIR]
  --with-clhep-lib=LIB     library name of libCLHEP.so [CLHEP|$CLHEP_LIB]

  --with-python-incdir=DIR  Python header dir [/usr/include/python(2.#)],
                            (location of pyconfig.h)
  --with-python-libdir=DIR  Python library dir [/usr/lib(64)]

  --with-boost-incdir=DIR   BOOST-C++ header dir [/usr/include],
                            (location of boost/)
  --with-boost-libdir=DIR   BOOST-C++ library dir [/usr/lib]
  --with-boost-python-lib=LIB library name of libboost_python.so [boost_python]

  --with-package-dir=DIR    Geant4 Package dir

  --with-extra-dir=DIR      Install path for extra packages [/usr/local]

  --with-xercesc-incdir=DIR Xerces-C header dir [/usr/include]
  --with-xercesc-libdir=DIR Xerces-C library dir [/usr/lib(64)]

Enable/disable options: prefix with either --enable- or --disable-
  openglx      OpenGLX support    [auto]
  openglxm     OpenGLXm support   [disable, $G4VIS_USE_OPENGLXM]
  raytracerx   RayTracerX support [disable, $G4VIS_USE_RAYTRACERX]

Supported Architectures:
  linux           for Linux gcc 3.x and 4.x (32bit)
  linux64         for Linux gcc 3.x and 4.x (64bit, alias to linuxx8664gcc)
  linuxx8664gcc   for AMD Opteron and Intel EM64T Linux gcc 3.x and 4.x
  macosx          for MacOSX with gcc (Tiger/Leopard and Xcode)
```

For example, you run it like

```
# ./configure linux64
  --with-g4-incdir=/opt/heplib/Geant4/geant4.9.3/include
  --with-g4-libdir=/opt/heplib/Geant4/geant4.9.3/slib/Linux-g++
  --with-clhep-incdir=/opt/heplib/CLHEP/2.0.4.5/include
  --with-clhep-libdir=/opt/heplib/CLHEP/2.0.4.5/lib
  --with-clhep-lib=CLHEP-2.0.4.5
```

The configure script automatically check your environment, and create `config/config.gmk`, which describes your envrionment. After executing the configure script successfully, then

```
# make
# make install
```

8.2. Using Geant4Py

PYTHONPATH environment variable should be set at tun time. **PYTHONPATH** environment variable indicates Python module search directories, given by a colon-separated list of directories. Practically, the variable is `(your g4py directory)/lib`.

8.2.1. Import Geant4

To use Geant4Py, you start with importing the module called "Geant4".

```
# python
```

```
Python 2.6.2 (r262:71600, Oct 24 2009, 03:15:21)
[GCC 4.4.1 [gcc-4_4-branch revision 150839]] on linux2
Type "help", "copyright", "credits" or "license" for more information.
>>> from Geant4 import *

*************************************************************
 Geant4 version Name: geant4-09-03        (18-December-2009)
                      Copyright : Geant4 Collaboration
                      Reference : NIM A 506 (2003), 250-303
                            WWW : http://cern.ch/geant4
*************************************************************

Visualization Manager instantiating...
>>>
```

8.2.2. Access to Geant4 Globals

When importing the Geant4 module, the `G4RunManager` object will be automatically instantiated. Geant4 singleton objects are also automatically instantiated. These singleton objects can be accessed by "gXXXX" variables, like "gRunManager".

```
                       gLossTableManager       gTerminate
gApplyUICommand        gMaterialTable          gTrackingManager
gControlExecute        gNistManager            gTransportationManager
gElementTable          gParticleIterator       gUImanager
gEmCalculator          gParticleTable          gVisManager
gEventManager          gProcessTable
gExceptionHandler      gProductionCutsTable
gG4Date                gRunManager
gG4VERSION_NUMBER      gRunManagerKernel
gG4Version             gStackManager
gGeometryManager       gStartUISession
gGetCurrentValues      gStateManager
```

8.2.3. Call Geant4 Methods

Once a Python object of a Geant4 class instantiated, Geant4 methods can be directly called the same way as in C++.

```
>>> from Geant4 import *

*************************************************************
 Geant4 version Name: geant4-09-03        (18-December-2009)
                      Copyright : Geant4 Collaboration
                      Reference : NIM A 506 (2003), 250-303
                            WWW : http://cern.ch/geant4
*************************************************************

Visualization Manager instantiating...

>>> print gRunManager.GetVersionString()
 Geant4 version Name: geant4-09-03    (18-December-2009)
```

8.3. Site-modules

Geant4Py provides additional utility modules called "g4py" in the directory `site-modules`. It consists of predifined geometries, materials, physics lists, primary generator actions, and so on.

8.3.1. *ezgeom* module

The *ezgeom* module provides an alternative way of defining simple geometry. An example code for defining a simple geometry is shown here:

```
import g4py.ezgeom
from g4py.ezgeom import G4EzVolume

def ConstructGeom():
  print "* Constructing geometry..."
  # reset world material
  air= G4Material.GetMaterial("G4_AIR")
  g4py.ezgeom.SetWorldMaterial(air)
```

```
  # a target box is placed
  global target
  target= G4EzVolume("Target")
  au= G4Material.GetMaterial("G4_Au")
  target.CreateTubeVolume(au, 0., 1.*cm, 1.*mm)
  target.PlaceIt(G4ThreeVector(0.,0.,-10.*cm))
```

8.3.2. *NISTmaterials* module

The *NISTmaterials* module provides an instant use of Geant4 NIST materials. An example code for creating NIST materials:

```
from Geant4 import *
import g4py.NISTmaterials

g4py.NISTmaterials.Construct()
print Geant4.gMaterialTable
```

8.3.3. *ParticleGun* module

The *ParticleGun* module provides a primary generator action with `G4ParticleGun`. An example code is shown here:

```
import g4py.ParticleGun

# normal way for constructing user primary generator action
#pgPGA= g4py.ParticleGun.ParticleGunAction()
#gRunManager.SetUserAction(pgPGA)
#pg= pgPGA.GetParticleGun()

# 2nd way, short-cut way
pg= g4py.ParticleGun.Construct()

# set parameters of particle gun
pg.SetParticleByName("e-")
pg.SetParticleEnergy(300.*MeV)
primary_position= G4ThreeVector(0.,0., -14.9*cm)
primary_direction= G4ThreeVector(0.2, 0., 1.)
pg.SetParticlePosition(primary_position)
pg.SetParticleMomentumDirection(primary_direction)
```

8.4. Examples

There are some examples of Geant4Py in the directories `"tests/"` and `"examples/"`.
In the `"tests/"` directory,

```
gtest01 : exposes a user application
gtest02 : test for using site-module packages
gtest03 : test for ezgeom package
gtest04 : test for getting command tree and command information
gtest05 : test for constructing CSG geometries in Python
gtest06 : test for constructing/visualizing boolean geoemtries
gtest07 : test for checking overlapped geometries
```

The `"examples/"` directory contains a set of examples of Geant4Py.

demos/water_phantom
: An example of "water phantom dosimetry". This demo program shows that a Geant4 application well coworks with Root on Python front end. VisManager, PrimaryGeneratorAction, UserAction-s, histogramming with Root are implemented in Python;

  - dose calculation in a water phantom
  - Python overloading of user actions
  - on-line histogramming with Root
  - visualization

education
: Educational examples with Graphical User Interface using `TKinter`

  * lesson1

  The first version of the courseware of the mass attenuation coefficient.

  * lesson2

  GUI interface of ExN03, which can control geometry configuration, intial particle condition, physics processes, cut value, magnetic field and visualization outputs.

emplot
: Examples of plotting photon cross sections and stopping powers with Root.

gdml
: Examples of writing/reading user's geometry to/from a GDML file

9. Geant4 Material Database

9.1. Pure Materials

```
=======================================================
  Z   Name    ChFormula        density(g/cm^3)     I(eV)
=======================================================
  1   G4_H                      8.3748e-05          19.2
  2   G4_He                     0.000166322         41.8
  3   G4_Li                     0.534               40
  4   G4_Be                     1.848               63.7
  5   G4_B                      2.37                76
  6   G4_C                      2                   81
  7   G4_N                      0.0011652           82
  8   G4_O                      0.00133151          95
  9   G4_F                      0.00158029         115
 10   G4_Ne                     0.000838505        137
 11   G4_Na                     0.971              149
 12   G4_Mg                     1.74               156
 13   G4_Al                     2.699              166
 14   G4_Si                     2.33               173
 15   G4_P                      2.2                173
 16   G4_S                      2                  180
 17   G4_Cl                     0.00299473         174
 18   G4_Ar                     0.00166201         188
 19   G4_K                      0.862              190
 20   G4_Ca                     1.55               191
 21   G4_Sc                     2.989              216
 22   G4_Ti                     4.54               233
 23   G4_V                      6.11               245
 24   G4_Cr                     7.18               257
 25   G4_Mn                     7.44               272
 26   G4_Fe                     7.874              286
 27   G4_Co                     8.9                297
 28   G4_Ni                     8.902              311
 29   G4_Cu                     8.96               322
 30   G4_Zn                     7.133              330
 31   G4_Ga                     5.904              334
 32   G4_Ge                     5.323              350
 33   G4_As                     5.73               347
 34   G4_Se                     4.5                348
 35   G4_Br                     0.0070721          343
 36   G4_Kr                     0.00347832         352
 37   G4_Rb                     1.532              363
 38   G4_Sr                     2.54               366
 39   G4_Y                      4.469              379
 40   G4_Zr                     6.506              393
 41   G4_Nb                     8.57               417
 42   G4_Mo                    10.22               424
 43   G4_Tc                    11.5                428
 44   G4_Ru                    12.41               441
 45   G4_Rh                    12.41               449
 46   G4_Pd                    12.02               470
```

```
 47   G4_Ag                    10.5               470
 48   G4_Cd                     8.65              469
 49   G4_In                     7.31              488
 50   G4_Sn                     7.31              488
 51   G4_Sb                     6.691             487
 52   G4_Te                     6.24              485
 53   G4_I                      4.93              491
 54   G4_Xe                     0.00548536        482
 55   G4_Cs                     1.873             488
 56   G4_Ba                     3.5               491
 57   G4_La                     6.154             501
 58   G4_Ce                     6.657             523
 59   G4_Pr                     6.71              535
 60   G4_Nd                     6.9               546
 61   G4_Pm                     7.22              560
 62   G4_Sm                     7.46              574
 63   G4_Eu                     5.243             580
 64   G4_Gd                     7.9004            591
 65   G4_Tb                     8.229             614
 66   G4_Dy                     8.55              628
 67   G4_Ho                     8.795             650
 68   G4_Er                     9.066             658
 69   G4_Tm                     9.321             674
 70   G4_Yb                     6.73              684
 71   G4_Lu                     9.84              694
 72   G4_Hf                    13.31              705
 73   G4_Ta                    16.654             718
 74   G4_W                     19.3               727
 75   G4_Re                    21.02              736
 76   G4_Os                    22.57              746
 77   G4_Ir                    22.42              757
 78   G4_Pt                    21.45              790
 79   G4_Au                    19.32              790
 80   G4_Hg                    13.546             800
 81   G4_Tl                    11.72              810
 82   G4_Pb                    11.35              823
 83   G4_Bi                     9.747             823
 84   G4_Po                     9.32              830
 85   G4_At                     9.32              825
 86   G4_Rn                     0.00900662        794
 87   G4_Fr                     1                 827
 88   G4_Ra                     5                 826
 89   G4_Ac                    10.07              841
 90   G4_Th                    11.72              847
 91   G4_Pa                    15.37              878
 92   G4_U                     18.95              890
 93   G4_Np                    20.25              902
 94   G4_Pu                    19.84              921
 95   G4_Am                    13.67              934
 96   G4_Cm                    13.51              939
 97   G4_Bk                    14                 952
 98   G4_Cf                    10                 966
```

9.2. NIST Compounds

```
============================================================
Ncomp  Name                      density(g/cm^3)     I(eV)
============================================================
 6     G4_A-150_TISSUE             1.127             65.1
             1     0.101327
             6     0.7755
             7     0.035057
             8     0.0523159
             9     0.017422
             20    0.018378
 3     G4_ACETONE                  0.7899            64.2
             1     0.104122
             6     0.620405
             8     0.275473
 2     G4_ACETYLENE                0.0010967         58.2
             1     0.077418
             6     0.922582
 3     G4_ADENINE                  1.35              71.4
             1     0.037294
             6     0.44443
```

```
            7     0.518276
13     G4_ADIPOSE_TISSUE_ICRP     0.92              63.2
            1     0.119477
            6     0.63724
            7     0.00797
            8     0.232333
            11    0.0005
            12    2e-05
            15    0.00016
            16    0.00073
            17    0.00119
            19    0.00032
            20    2e-05
            26    2e-05
            30    2e-05
 4     G4_AIR                     0.00120479        85.7
            6     0.000124
            7     0.755268
            8     0.231781
            18    0.012827
 4     G4_ALANINE                 1.42              71.9
            1     0.0791899
            6     0.404439
            7     0.157213
            8     0.359159
 2     G4_ALUMINUM_OXIDE Al_2O_3  3.97             145.2
            8     0.470749
            13    0.529251
 3     G4_AMBER                   1.1               63.2
            1     0.10593
            6     0.788974
            8     0.105096
 2     G4_AMMONIA                 0.000826019       53.7
            1     0.177547
            7     0.822453
 3     G4_ANILINE                 1.0235            66.2
            1     0.075759
            6     0.773838
            7     0.150403
 2     G4_ANTHRACENE              1.283             69.5
            1     0.05655
            6     0.94345
 6     G4_B-100_BONE              1.45              85.9
            1     0.0654709
            6     0.536944
            7     0.0215
            8     0.032085
            9     0.167411
            20    0.176589
 3     G4_BAKELITE                1.25              72.4
            1     0.057441
            6     0.774591
            8     0.167968
 2     G4_BARIUM_FLUORIDE         4.89             375.9
            9     0.21672
            56     0.78328
 3     G4_BARIUM_SULFATE          4.5              285.7
            8     0.274212
            16    0.137368
            56    0.58842
 2     G4_BENZENE                 0.87865           63.4
            1     0.077418
            6     0.922582
 2     G4_BERYLLIUM_OXIDE         3.01              93.2
            4     0.36032
            8     0.63968
 3     G4_BGO                     7.13             534.1
            8     0.154126
            32    0.17482
            83    0.671054
14     G4_BLOOD_ICRP              1.06              75.2
            1     0.101866
            6     0.10002
            7     0.02964
            8     0.759414
            11    0.00185
            12    4e-05
```

```
              14    3e-05
              15    0.00035
              16    0.00185
              17    0.00278
              19    0.00163
              20    6e-05
              26    0.00046
              30    1e-05
 8     G4_BONE_COMPACT_ICRU       1.85              91.9
              1     0.063984
              6     0.278
              7     0.027
              8     0.410016
              12    0.002
              15    0.07
              16    0.002
              20    0.147
 9     G4_BONE_CORTICAL_ICRP      1.85             106.4
              1     0.047234
              6     0.14433
              7     0.04199
              8     0.446096
              12    0.0022
              15    0.10497
              16    0.00315
              20    0.20993
              30    0.0001
 2     G4_BORON_CARBIDE           2.52              84.7
              5     0.78261
              6     0.21739
 2     G4_BORON_OXIDE             1.812             99.6
              5     0.310551
              8     0.689449
13     G4_BRAIN_ICRP              1.03              73.3
              1     0.110667
              6     0.12542
              7     0.01328
              8     0.737723
              11    0.00184
              12    0.00015
              15    0.00354
              16    0.00177
              17    0.00236
              19    0.0031
              20    9e-05
              26    5e-05
              30    1e-05
 2     G4_BUTANE                  0.00249343        48.3
              1     0.173408
              6     0.826592
 3     G4_N-BUTYL_ALCOHOL         0.8098            59.9
              1     0.135978
              6     0.648171
              8     0.215851
 5     G4_C-552                   1.76              86.8
              1     0.02468
              6     0.501611
              8     0.004527
              9     0.465209
              14    0.003973
 2     G4_CADMIUM_TELLURIDE       6.2              539.3
              48    0.468355
              52    0.531645
 3     G4_CADMIUM_TUNGSTATE       7.9              468.3
              8     0.177644
              48    0.312027
              74    0.510329
 3     G4_CALCIUM_CARBONATE       2.8              136.4
              6     0.120003
              8     0.479554
              20    0.400443
 2     G4_CALCIUM_FLUORIDE        3.18             166
              9     0.486659
              20    0.513341
 2     G4_CALCIUM_OXIDE           3.3              176.1
              8     0.285299
              20    0.714701
```

```
 3     G4_CALCIUM_SULFATE          2.96             152.3
              8     0.470095
              16    0.235497
              20    0.294408
 3     G4_CALCIUM_TUNGSTATE        6.062            395
              8     0.22227
              20    0.139202
              74    0.638528
 2     G4_CARBON_DIOXIDE  CO_2     0.00184212        85
              6     0.272916
              8     0.727084
 2     G4_CARBON_TETRACHLORIDE     1.594            166.3
              6     0.078083
              17    0.921917
 3     G4_CELLULOSE_CELLOPHANE     1.42              77.6
              1     0.062162
              6     0.444462
              8     0.493376
 3     G4_CELLULOSE_BUTYRATE       1.2               74.6
              1     0.067125
              6     0.545403
              8     0.387472
 4     G4_CELLULOSE_NITRATE        1.49              87
              1     0.029216
              6     0.271296
              7     0.121276
              8     0.578212
 5     G4_CERIC_SULFATE            1.03              76.7
              1     0.107596
              7     0.0008
              8     0.874976
              16    0.014627
              58    0.002001
 2     G4_CESIUM_FLUORIDE          4.115            440.7
              9     0.125069
              55    0.874931
 2     G4_CESIUM_IODIDE            4.51             553.1
              53    0.488451
              55    0.511549
 3     G4_CHLOROBENZENE            1.1058            89.1
              1     0.044772
              6     0.640254
              17    0.314974
 3     G4_CHLOROFORM               1.4832           156
              1     0.008443
              6     0.100613
              17     0.890944
10     G4_CONCRETE                 2.3              135.2
              1     0.01
              6     0.001
              8     0.529107
              11    0.016
              12    0.002
              13    0.033872
              14    0.337021
              19    0.013
              20    0.044
              26    0.014
 2     G4_CYCLOHEXANE             0.779              56.4
              1     0.143711
              6     0.856289
 3     G4_1,2-DICHLOROBENZENE     1.3048            106.5
              1     0.027425
              6     0.490233
              17     0.482342
 4     G4_DICHLORODIETHYL_ETHER   1.2199            103.3
              1     0.0563811
              6     0.335942
              8     0.111874
              17    0.495802
 3     G4_1,2-DICHLOROETHANE      1.2351             111.9
              1     0.04074
              6     0.242746
              17     0.716514
 3     G4_DIETHYL_ETHER           0.71378             60
              1     0.135978
              6     0.648171
```

```
            8     0.215851
4     G4_N,N-DIMETHYL_FORMAMIDE 0.9487              66.6
            1     0.096523
            6     0.492965
            7     0.191625
            8     0.218887
4     G4_DIMETHYL_SULFOXIDE     1.1014              98.6
            1     0.077403
            6     0.307467
            8     0.204782
            16    0.410348
2     G4_ETHANE                 0.00125324          45.4
            1     0.201115
            6     0.798885
3     G4_ETHYL_ALCOHOL          0.7893              62.9
            1     0.131269
            6     0.521437
            8     0.347294
3     G4_ETHYL_CELLULOSE        1.13                69.3
            1     0.090027
            6     0.585182
            8     0.324791
2     G4_ETHYLENE               0.00117497          50.7
            1     0.143711
            6     0.856289
4     G4_EYE_LENS_ICRP          1.1                 73.3
            1     0.099269
            6     0.19371
            7     0.05327
            8     0.653751
2     G4_FERRIC_OXIDE           5.2                 227.3
            8     0.300567
            26    0.699433
2     G4_FERROBORIDE            7.15                261
            5     0.162174
            26    0.837826
2     G4_FERROUS_OXIDE          5.7                 248.6
            8     0.222689
            26    0.777311
7     G4_FERROUS_SULFATE        1.024               76.4
            1     0.108259
            7     2.7e-05
            8     0.878636
            11    2.2e-05
            16    0.012968
            17    3.4e-05
            26    5.4e-05
3     G4_FREON-12               1.12                143
            6     0.099335
            9     0.314247
            17    0.586418
3     G4_FREON-12B2             1.8                 284.9
            6     0.057245
            9     0.181096
            35    0.761659
3     G4_FREON-13               0.95                126.6
            6     0.114983
            9     0.545621
            17    0.339396
3     G4_FREON-13B1             1.5                 210.5
            6     0.080659
            9     0.382749
            35    0.536592
3     G4_FREON-13I1             1.8                 293.5
            6     0.061309
            9     0.290924
            53    0.647767
3     G4_GADOLINIUM_OXYSULFIDE  7.44                493.3
            8     0.084528
            16    0.08469
            64    0.830782
2     G4_GALLIUM_ARSENIDE       5.31                384.9
            31    0.482019
            33    0.517981
5     G4_GEL_PHOTO_EMULSION     1.2914              74.8
            1     0.08118
            6     0.41606
```

```
            7     0.11124
            8     0.38064
            16    0.01088
6     G4_Pyrex_Glass              2.23              134
            5     0.0400639
            8     0.539561
            11    0.0281909
            13    0.011644
            14    0.377219
            19    0.00332099
5     G4_GLASS_LEAD               6.22              526.4
            8     0.156453
            14    0.080866
            22    0.008092
            33    0.002651
            82    0.751938
4     G4_GLASS_PLATE              2.4               145.4
            8     0.4598
            11    0.0964411
            14    0.336553
            20    0.107205
3     G4_GLUCOSE                  1.54               77.2
            1     0.071204
            6     0.363652
            8     0.565144
4     G4_GLUTAMINE                1.46               73.3
            1     0.0689651
            6     0.410926
            7     0.191681
            8     0.328427
3     G4_GLYCEROL                 1.2613             72.6
            1     0.0875539
            6     0.391262
            8     0.521184
4     G4_GUANINE                  1.58               75
            1     0.033346
            6     0.39738
            7     0.463407
            8     0.105867
4     G4_GYPSUM                   2.32              129.7
            1     0.023416
            8     0.557572
            16    0.186215
            20    0.232797
2     G4_N-HEPTANE                0.68376            54.4
            1     0.160937
            6     0.839063
2     G4_N-HEXANE                 0.6603             54
            1     0.163741
            6     0.836259
4     G4_KAPTON                   1.42               79.6
            1     0.026362
            6     0.691133
            7     0.07327
            8     0.209235
3     G4_LANTHANUM_OXYBROMIDE     6.28              439.7
            8     0.068138
            35    0.340294
            57    0.591568
3     G4_LANTHANUM_OXYSULFIDE     5.86              421.2
            8     0.0936
            16    0.093778
            57    0.812622
2     G4_LEAD_OXIDE               9.53              766.7
            8     0.071682
            82    0.928318
3     G4_LITHIUM_AMIDE            1.178              55.5
            1     0.087783
            3     0.302262
            7     0.609955
3     G4_LITHIUM_CARBONATE        2.11               87.9
            3     0.187871
            6     0.16255
            8     0.649579
2     G4_LITHIUM_FLUORIDE         2.635              94
            3     0.267585
            9     0.732415
```

```
 2     G4_LITHIUM_HYDRIDE          0.82              36.5
             1     0.126797
             3     0.873203
 2     G4_LITHIUM_IODIDE           3.494            485.1
             3     0.051858
             53    0.948142
 2     G4_LITHIUM_OXIDE            2.013             73.6
             3     0.46457
             8     0.53543
 3     G4_LITHIUM_TETRABORATE      2.44              94.6
             3     0.082085
             5     0.25568
             8     0.662235
13     G4_LUNG_ICRP                1.05              75.3
             1     0.101278
             6     0.10231
             7     0.02865
             8     0.757072
             11    0.00184
             12    0.00073
             15    0.0008
             16    0.00225
             17    0.00266
             19    0.00194
             20    9e-05
             26    0.00037
             30    1e-05
 5     G4_M3_WAX                   1.05              67.9
             1     0.114318
             6     0.655824
             8     0.0921831
             12    0.134792
             20    0.002883
 3     G4_MAGNESIUM_CARBONATE      2.958            118
             6     0.142455
             8     0.569278
             12    0.288267
 2     G4_MAGNESIUM_FLUORIDE       3                 134.3
             9     0.609883
             12    0.390117
 2     G4_MAGNESIUM_OXIDE          3.58              143.8
             8     0.396964
             12    0.603036
 3     G4_MAGNESIUM_TETRABORATE    2.53              108.3
             5     0.240837
             8     0.62379
             12    0.135373
 2     G4_MERCURIC_IODIDE          6.36              684.5
             53    0.55856
             80    0.44144
 2     G4_METHANE                  0.000667151        41.7
             1     0.251306
             6     0.748694
 3     G4_METHANOL                 0.7914             67.6
             1     0.125822
             6     0.374852
             8     0.499326
 5     G4_MIX_D_WAX                0.99               60.9
             1     0.13404
             6     0.77796
             8     0.03502
             12    0.038594
             22    0.014386
 6     G4_MS20_TISSUE              1                  75.1
             1     0.081192
             6     0.583442
             7     0.017798
             8     0.186381
             12    0.130287
             17    0.0009
13     G4_MUSCLE_SKELETAL_ICRP     1.04               75.3
             1     0.100637
             6     0.10783
             7     0.02768
             8     0.754773
             11    0.00075
             12    0.00019
```

```
             15    0.0018
             16    0.00241
             17    0.00079
             19    0.00302
             20    3e-05
             26    4e-05
             30    5e-05
9      G4_MUSCLE_STRIATED_ICRU    1.04              74.7
             1     0.101997
             6     0.123
             7     0.035
             8     0.729003
             11    0.0008
             12    0.0002
             15    0.002
             16    0.005
             19    0.003
4      G4_MUSCLE_WITH_SUCROSE     1.11              74.3
             1     0.0982341
             6     0.156214
             7     0.035451
             8     0.710101
4      G4_MUSCLE_WITHOUT_SUCROSE  1.07              74.2
             1     0.101969
             6     0.120058
             7     0.035451
             8     0.742522
2      G4_NAPHTHALENE             1.145             68.4
             1     0.062909
             6     0.937091
4      G4_NITROBENZENE            1.19867           75.8
             1     0.040935
             6     0.585374
             7     0.113773
             8     0.259918
2      G4_NITROUS_OXIDE           0.00183094        84.9
             7     0.636483
             8     0.363517
4      G4_NYLON-8062              1.08              64.3
             1     0.103509
             6     0.648416
             7     0.0995361
             8     0.148539
4      G4_NYLON-6/6               1.14              63.9
             1     0.097976
             6     0.636856
             7     0.123779
             8     0.141389
4      G4_NYLON-6/10              1.14              63.2
             1     0.107062
             6     0.680449
             7     0.099189
             8     0.1133
4      G4_NYLON-11_RILSAN         1.425             61.6
             1     0.115476
             6     0.720818
             7     0.0764169
             8     0.0872889
2      G4_OCTANE                  0.7026            54.7
             1     0.158821
             6     0.841179
2      G4_PARAFFIN                0.93              55.9
             1     0.148605
             6     0.851395
2      G4_N-PENTANE               0.6262            53.6
             1     0.167635
             6     0.832365
8      G4_PHOTO_EMULSION          3.815            331
             1     0.0141
             6     0.072261
             7     0.01932
             8     0.066101
             16    0.00189
             35    0.349103
             47    0.474105
             53    0.00312
2      G4_PLASTIC_SC_VINYLTOLUENE 1.032             64.7
```

```
            1     0.085
            6     0.915
2     G4_PLUTONIUM_DIOXIDE      11.46             746.5
            8     0.118055
            94    0.881945
3     G4_POLYACRYLONITRILE       1.17              69.6
            1     0.0569829
            6     0.679055
            7     0.263962
3     G4_POLYCARBONATE           1.2               73.1
            1     0.055491
            6     0.755751
            8     0.188758
3     G4_POLYCHLOROSTYRENE       1.3               81.7
            1     0.061869
            6     0.696325
            17    0.241806
2     G4_POLYETHYLENE  (C_2H_4)_N-Polyethylene
                                0.94              57.4
            1     0.143711
            6     0.856289
3     G4_MYLAR                  1.4               78.7
            1     0.041959
            6     0.625016
            8     0.333025
3     G4_PLEXIGLASS             1.19              74
            1     0.080538
            6     0.599848
            8     0.319614
3     G4_POLYOXYMETHYLENE       1.425             77.4
            1     0.067135
            6     0.400017
            8     0.532848
2     G4_POLYPROPYLENE  (C_2H_4)_N-Polypropylene
                                0.9               56.5
            1     0.143711
            6     0.856289
2     G4_POLYSTYRENE            1.06              68.7
            1     0.077418
            6     0.922582
2     G4_TEFLON                 2.2               99.1
            6     0.240183
            9     0.759817
3     G4_POLYTRIFLUOROCHLOROETHYLENE
                                2.1              120.7
            6     0.20625
            9     0.489354
            17    0.304395
3     G4_POLYVINYL_ACETATE       1.19              73.7
            1     0.070245
            6     0.558066
            8     0.371689
3     G4_POLYVINYL_ALCOHOL       1.3               69.7
            1     0.091517
            6     0.545298
            8     0.363185
3     G4_POLYVINYL_BUTYRAL       1.12              67.2
            1     0.092802
            6     0.680561
            8     0.226637
3     G4_POLYVINYL_CHLORIDE      1.3              108.2
            1     0.04838
            6     0.38436
            17    0.56726
3     G4_POLYVINYLIDENE_CHLORIDE 1.7              134.3
            1     0.020793
            6     0.247793
            17    0.731414
3     G4_POLYVINYLIDENE_FLUORIDE 1.76              88.8
            1     0.03148
            6     0.375141
            9     0.593379
4     G4_POLYVINYL_PYRROLIDONE   1.25              67.7
            1     0.081616
            6     0.648407
            7     0.126024
            8     0.143953
```

```
 2     G4_POTASSIUM_IODIDE        3.13            431.9
              19    0.235528
              53    0.764472
 2     G4_POTASSIUM_OXIDE         2.32            189.9
              8     0.169852
              19    0.830148
 2     G4_PROPANE                 0.00187939       47.1
              1     0.182855
              6     0.817145
 2     G4_lPROPANE                0.43             52
              1     0.182855
              6     0.817145
 3     G4_N-PROPYL_ALCOHOL        0.8035           61.1
              1     0.134173
              6     0.599595
              8     0.266232
 3     G4_PYRIDINE                0.9819           66.2
              1     0.06371
              6     0.759217
              7     0.177073
 2     G4_RUBBER_BUTYL            0.92             56.5
              1     0.143711
              6     0.856289
 2     G4_RUBBER_NATURAL          0.92             59.8
              1     0.118371
              6     0.881629
 3     G4_RUBBER_NEOPRENE         1.23             93
              1     0.05692
              6     0.542646
              17    0.400434
 2     G4_SILICON_DIOXIDE  SiO_2  2.32            139.2
              8     0.532565
              14    0.467435
 2     G4_SILVER_BROMIDE          6.473            486.6
              35    0.425537
              47    0.574463
 2     G4_SILVER_CHLORIDE         5.56             398.4
              17    0.247368
              47    0.752632
 3     G4_SILVER_HALIDES          6.47             487.1
              35    0.422895
              47    0.573748
              53    0.003357
 2     G4_SILVER_IODIDE           6.01             543.5
              47    0.459458
              53    0.540542
13     G4_SKIN_ICRP               1.1               72.7
              1     0.100588
              6     0.22825
              7     0.04642
              8     0.619002
              11    7e-05
              12    6e-05
              15    0.00033
              16    0.00159
              17    0.00267
              19    0.00085
              20    0.00015
              26    1e-05
              30    1e-05
 3     G4_SODIUM_CARBONATE        2.532            125
              6     0.113323
              8     0.452861
              11    0.433815
 2     G4_SODIUM_IODIDE           3.667            452
              11    0.153373
              53    0.846627
 2     G4_SODIUM_MONOXIDE         2.27             148.8
              8     0.258143
              11    0.741857
 3     G4_SODIUM_NITRATE          2.261           114.6
              7     0.164795
              8     0.56472
              11    0.270485
 2     G4_STILBENE                0.9707           67.7
              1     0.067101
              6     0.932899
```

```
 3     G4_SUCROSE                1.5805          77.5
              1     0.064779
              6     0.42107
              8     0.514151
 2     G4_TERPHENYL              1.234           71.7
              1     0.044543
              6     0.955457
13     G4_TESTES_ICRP            1.04            75
              1     0.104166
              6     0.09227
              7     0.01994
              8     0.773884
              11    0.00226
              12    0.00011
              15    0.00125
              16    0.00146
              17    0.00244
              19    0.00208
              20    0.0001
              26    2e-05
              30    2e-05
 2     G4_TETRACHLOROETHYLENE    1.625           159.2
              6     0.144856
              17    0.855144
 2     G4_THALLIUM_CHLORIDE      7.004           690.3
              17    0.147822
              81    0.852178
13     G4_TISSUE_SOFT_ICRP       1               72.3
              1     0.104472
              6     0.23219
              7     0.02488
              8     0.630238
              11    0.00113
              12    0.00013
              15    0.00133
              16    0.00199
              17    0.00134
              19    0.00199
              20    0.00023
              26    5e-05
              30    3e-05
 4     G4_TISSUE_SOFT_ICRU-4     1               74.9
              1     0.101172
              6     0.111
              7     0.026
              8     0.761828
 4     G4_TISSUE-METHANE         0.00106409      61.2
              1     0.101869
              6     0.456179
              7     0.035172
              8     0.40678
 4     G4_TISSUE-PROPANE         0.00182628      59.5
              1     0.102672
              6     0.56894
              7     0.035022
              8     0.293366
 2     G4_TITANIUM_DIOXIDE       4.26            179.5
              8     0.400592
              22    0.599408
 2     G4_TOLUENE                0.8669          62.5
              1     0.08751
              6     0.91249
 3     G4_TRICHLOROETHYLENE      1.46            148.1
              1     0.007671
              6     0.182831
              17    0.809498
 4     G4_TRIETHYL_PHOSPHATE     1.07            81.2
              1     0.082998
              6     0.395628
              8     0.351334
              15    0.17004
 2     G4_TUNGSTEN_HEXAFLUORIDE  2.4             354.4
              9     0.382723
              74    0.617277
 2     G4_URANIUM_DICARBIDE      11.28           752
              6     0.091669
              92    0.908331
```

```
 2     G4_URANIUM_MONOCARBIDE    13.63           862
              6     0.048036
              92    0.951964
 2     G4_URANIUM_OXIDE          10.96           720.6
              8     0.118502
              92    0.881498
 4     G4_UREA                    1.323           72.8
              1     0.067131
              6     0.199999
              7     0.466459
              8     0.266411
 4     G4_VALINE                  1.23            67.7
              1     0.0946409
              6     0.512644
              7     0.119565
              8     0.27315
 3     G4_VITON                   1.8             98.6
              1     0.009417
              6     0.280555
              9     0.710028
 2     G4_WATER  H_2O               1               75
              1     0.111894
              8     0.888106
 2     G4_WATER_VAPOR  H_2O-Gas   0.000756182     71.6
              1     0.111894
              8     0.888106
 2     G4_XYLENE                  0.87            61.8
              1     0.094935
              6     0.905065
 1     G4_GRAPHITE  Graphite     1.7             78
```

9.3. HEP Materials

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=========================================================
Ncomp  Name                     density(g/cm^3)     I(eV)
=========================================================
 1     G4_lH2                   0.0708               21.8
 1     G4_lAr                   1.396               188
 1     G4_lKr                   2.418               352
 1     G4_lXe                   2.953               482
 3     G4_PbWO4                 8.28                  0
              8     0.140637
              82    0.455366
              74    0.403998
 1     G4_Galactic              1e-25                21.8
```

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